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THIN DENSE CHROME BEARING INSERTION PROGRAM

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This report includes the results of program efforts to develop and introduce a nodular Thin Dense Chrome (TDC) plating process for aircraft engine mainshaft bearings. Program objectives included development of a Thin Dense Chrome material/process specification and completing a thorough evaluation of all potential risks associated with introducing TDC coated bearings into field engine applications.

A comprehensive series of subscale and full scale tests were completed to evaluate the capabilities of TDC coated bearings at various in–service operating conditions.

TDC coated bearings demonstrated improved corrosion and contamination resistance. TDC coated bearings also demonstrated acceptable performance during thermal cycle, oil–off, and induced defect conditions. However, the TDC coating performance did not meet the required objectives in the areas of rolling contact fatigue life, skid damage resistance, engine assembly damage tolerance, and engine operational endurance.

Based on the results of this program, it was concluded that TDC coated bearings provided too great of a risk for insertion into the mainshaft bearing positions of military aircraft engines.

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1.0 Summary

This report includes the results of program efforts to develop and evaluate a nodular Thin Dense Chrome (TDC) plating process for main shaft bearings used in existing F101 and F110 military engine applications. Program objectives included development of a TDC specification and thoroughly evaluating all potential risks associated with introducing TDC coated bearings into in–service F101 and F110 engine applications.

To achieve the program objectives, a comprehensive group of subscale and full scale tests were completed. Subscale tests evaluated TDC coating quality characteristics (thickness, topography, adhesion, residual stress and hydrogen embrittlement), corrosion resistance, wear characteristics, thermal shock capability, and rolling contact fatigue life. Full scale testing demonstrated TDC coating operational endurance, contamination resistance, oil–off capabilities, skid damage resistance, induced defect tolerance, thermal cycle capability, corrosion resistance, engine assembly damage tolerance, and engine endurance capabilities.

TDC coated bearings demonstrated improved corrosion and contamination resistance. In addition, TDC coated bearings demonstrated acceptable performance characteristics during thermal cyclic, oil–off and induced defect conditions. However, the TDC coating characteristics and performance did not meet the required objectives in several areas. Subscale testing of TDC coated bearings resulted in failures in the areas of thickness, topography, salt spray corrosion, hydrogen embrittlement, and rolling contact fatigue. Full scale TDC bearings did not meet the required objectives relative to skid damage resistance, engine assembly damage tolerance and engine operational endurance capabilities. TDC coated bearings were more susceptible to damage from skidding conditions and engine assembly processes. Skid and assembly damage resulted in bearing failures or rejections during engine testing.

Based on the results of this program, it was concluded that TDC coated bearings provided too great of a risk for insertion into F101 and F110 engine applications.

2.0 Introduction

GE Aircraft Engines completed this program under contract F33615–92–C–2208. The Thin Dense Chrome Bearing Insertion Program was a 54–month effort and was performed under the guidance of Jon Dell, USAF Project Engineer. The objective of the program was to develop a material/process specification for applying Thin Dense Chrome to aerospace quality mainshaft bearings and to complete qualification testing to substantiate insertion of TDC coated mainshaft bearings into the F101 and F110 military gas turbine engines. As part of this effort, a thorough evaluation of the benefits and risks associated with TDC needed to be completed prior to introducing TDC bearings to fielded engines.

2.1 Program Description

Phase I included development of a TDC specification, qualifying the TDC coating process for two domestic bearing suppliers and preparation of rationale and test plans to demonstrate compliance with current engine/bearing specification requirements. Phase II included full scale TDC coated bearing rig and engine testing. Due to hardware delivery lead time constraints the two phases were conducted in parallel.

The program was organized in the following tasks under two phases:

Phase I

Task 1 – Specification for TDC Coating

Task 2 – Bearing Source/Specification Approval Testing

Task 3 – Specification Review

Task 4 – Test Plan/Design Review

Phase II

Task 5 – Full Scale Engine Bearing Qualification Testing

Task 6 – Engine AMT (Accelerated Mission Testing)

Technology Insertion

2.2 Background

The benefits provided by TDC coated bearings were first demonstrated for gas turbine application under Contract F33615–84–C–2430, managed by WL/POSL. In this contract, GEAE showed that coating bearings with TDC could substantially increase corrosion resistance, improve surface damage tolerance (namely, increase resistance to scratching and pitting), and provide increased rolling contact fatigue life in a contaminated oil environment. TDC was compared to other coatings, such as TiN and to implantation species such as Ta+ and Cr+. The TDC was found to be superior to these other candidates in terms of corrosion protection and, from an overall perspective, it was considered to be a realistic and viable proposition that could easily be applied in a production environment (unlike many of the other candidates).

TDC coated bearings were expected to offer significant improvements in reliability and maintenance when compared to conventional uncoated bearings; these improvements were expected to be achieved with low operational risk. For example, in 1989 a TDC coated bearing from Contract F33615–84–C–2430 was installed in an F101 component improvement program engine. That bearing successfully completed 482 hours of engine test time. Additionally, TDC bearings had been tested in the Aero Propulsion and Power Directorate's Advanced Turbine Engine Gas Generator (ATEGG) program and had successfully completed 160 hours of engine test time. This accu-

mulated engine time was expected to ensure the full transitioning of the technology into service with relatively low risk.

The combined test results from Contract F33615–84–C–2430 and the two engine tests noted above had been so promising that transitioning this technology into production engines was considered the logical next step. However, potential risks needed to be thoroughly evaluated and tested to ensure a low risk insertion into engines in the field. For example, with respect to surface preparation and residual stress patterns, the TDC plating process needed to be carefully controlled in order to achieve consistently good results. Torrington–Fafnir Bearing Company with their Fafcote – TDC process had demonstrated successful application of TDC to aerospace quality bearings. The other bearing suppliers needed to demonstrate similar consistent and controlled processes. Part of this program focused on the optimization of the TDC process and the generation of a new specification so that all bearing suppliers could potentially be qualified with TDC coated bearings. This program included all qualification steps required to fully assess potential risks and introduce TDC into engine service.

2.3 Technology Status

TDC coatings emerged during the late 1980's as the leading candidate in surface enhancement of bearings and was expected to be key to future improvements in rolling contact fatigue life. However, whenever a highly loaded contact surface, such as an aircraft engine bearing raceway, was coated with a protective layer, caution needed to be applied and testing completed to ensure that negative effects were not unnecessarily introduced into the bearing system. This program generated data to assess bearing performance at engine operating conditions.

Figure 1 shows an overview of the potential risks associated with TDC coated bearings. This overview indicates how each of the possible failure modes would be evaluated to establish a high degree of confidence prior to introducing TDC coated bearing systems.

2.4 TDC Coating Technical Description

TDC is an electro–deposited coating. It is plated onto the surface of bearings that are usually made to be the cathodes in the plating bath. Bath chemistry and temperature, current density; plating time, and surface preparation are critical parameters in the production of dense crack–free coatings. Generally, TDC is plated to a thickness of between 0.000050 to 0.000100 inch only. (More traditional Cr coatings often exceed 0.000200 inch making them more susceptible to flaking during rolling contact at high contact stress.) Current density is also closely controlled.

There have been no previous recorded cases of hydrogen embrittlement after TDC application. It is believed that this is because of the relatively short time needed in the plating bath to achieve the required thickness resulting in minimal hydrogen absorption. However, whenever a ferrous material is electrolytically plated, there is a potential for hydrogen embrittlement. For this reason, a postplating bake is mandatory for aerospace applications. The exact temperature and time for the bake cycle may vary from supplier to supplier depending on specific requirements. Variation even exists among controlling specifications (for example, AMS 2438 calls out 375°F for not less than 5 hours while Federal Specification QQC320 requires 375°F for at least 23 hours for materials above 40 Rc hardness, like bearing materials). Part of this program included defining the post–plate baking conditions for aerospace quality TDC coated bearings.

Properly processed TDC, in addition to being crack–free (at 500X magnification) and dense, usually exhibits a dull gray luster and has surface hardness equivalent to 70 to 72 Rc.

Potential Risks	Risk Abatement Plans
Will TDC Come Off? Due to: Cracking, Wear? abrasion,fatigue thermal shock, corrosion, high loads, tensile, residual stress, nonuniformity, poor adhesion	**Quality Control/Assurance** • Acceptance Tests (Each Lot): Adhesion thickness surface quality • Periodic Tests: Hardness, wear/abrasion, corrosion, H_2 embrittlement • Preproduction Tests: RC fatigue, HC fatigue, thermal cycling
Will TDC Cause H_2 Embrittlement of Coat-ing or Substrate?	**Specification Requirements for Optimum Post Heat Treatment** • H_2 diffusion/safe removal bake cycle mandatory • H_2 embrittlement testing – mandatory for production start then periodic
Will TDC Negate Bearing Properties? Is it compatible with bearing materials? Will TDC shorten bearing life? Is the failure mode acceptable?	**Specification and Full Scale Bearing Rig/Engine Test** • Endurance tests • Oil out tests • Skidding tests • Oil contamination tests • Assembly damage assessment test (Engine/rig tests all bearing positions) • Preproduction tests: Subscale bearing contact fatigue tests

Figure 1. Potential Risks Associated with Thin Dense Chrome Coated Bearings.
TDC Coatings require thorough evaluation prior to technology insertion.

Surface topography is usually defined by optical microscopy at 500X and requires nodularity compared with standards for acceptance. Surface roughness is controlled between 5 to 8 µin. For bearing races, this means that surface roughness in the rolling zone will increase from approximately 3–5 to 5–8 µin and for other surfaces, such as shoulders where roughness is approximately 12 µin, the surface finish will improve slightly. Surfaces about 12 µin will not change roughness after TDC plating.

2.5 Technical Objective Summary

TDC technology development reached a point where it was thought to be ready for full transition to field applications. To substantiate the full transition of the technology to the F101 and F110 family of engines, a thorough evaluation of the benefits and risks associated with TDC was completed. The program had two main objectives:

1. Develop a GE/Air Force Specification for uniformity and quality control of TDC coated main shaft turbine engine bearings and qualify two bearing suppliers to the specification requirements.

2. Perform rig testing, engine testing, and inspections required to qualify TDC bearings at all main shaft bearing positions in the F101 and F110 military production engines.

The program included working with two domestic bearing suppliers [MRC/SKF and Split Ball Bearing(SBB)/Timkin] to procure bearings for testing.

3.0 TDC Specification Development

As part of the Vendor Qualification Plan, an internal GE Specification (see Appendix E) was written to define limits on characteristics of the TDC coating and process for aerospace bearing applications. The specification included both processing related items such as surface preparation, stress relieving, cleaning of the parts being plated, and guidelines for postplating baking as well as coating properties such as TDC thickness, topography, thermal shock testing, and rolling contact fatigue (RCF) properties.

The specification was based on practices and properties which had produced positive TDC properties.

4.0 Subscale Vendor Qualification Testing

4.1 Test Procedures

4.1.1 Thickness Checks

Thickness checks were performed using both nondestructive techniques such as X–ray Fluorescence (XRF), and destructively using techniques such as the Kocour (Coulometric Method) or measuring the plating thickness by examining a specimens cross section per ASTM B 487. Thickness specifications were for functional areas to have between 40 and 100 μin of TDC and other areas to be between 40 and 250 μin.

4.1.2 Topography

Specimens were examined optically at 15X and 50X as well as by the Scanning Electron Microscope at 500X. A specimen was considered to have passed the topography check if its functional surfaces and near functional surfaces were free of cracks, pinholes, peeling, porosity, discontinuities or irregular isolated chromium deposits when examined at 15X and 50X, and exhibited a nodular, crack free, chrome cluster free appearance when examined at 500X.

4.1.3 Corrosion Testing

Corrosion testing was performed in accordance to ASTM–B–117, 24–hour salt spray. A TDC plated inner ring was used as the test specimen. A specimen was considered to have passed if it was free of corrosion, except for a few isolated pits in nonfunctional areas.

4.1.4 Hydrogen Embrittlement

Hydrogen embrittlement testing was performed in accordance to ASTM–F–519, for notched tensile specimens (Type 1A). A plated specimen was considered to have passed the test when it has sustained a load equal to 75% of the average load required to fail an unplated notched specimen for a minimum of 200 hours.

4.1.5 Wear Testing

Wear resistance was performed in accordance to FED–STD–141, Method 6192, using a Taber specimen. Each of three test specimens were subjected to a 1000 gram load for 5,000 cycles using a Taber abrasion tester with CS–10 wheels. The wear index scale is a normalizing technique used to compare data from different tests which may contain various cycles of abrasion. The index number is calculated by dividing the average weight loss in milligrams by the number of abrasive cycles in thousands. It is an indicator of the rate of wear the specimen has undergone. A set of specimens were considered to have passed the test if the average weight loss was ≤6 mg, or an average wear index of ≤1.2.

4.1.6 Adhesion Testing

Adhesion testing was performed in accordance to ASTM 2438. A sample was considered to have passed if it was free of delamination or flaked off TDC after the bend test.

4.1.7 Thermal Shock Testing

Thermal shock testing was performed by exposing subscale bearing samples to a series of 10 rapid thermal cycles between –65°F and +600°F.

4.1.8 Residual Stress

Residual stress of the TDC coating was determined using X–ray techniques. The coating passed this test if it was shown to be in a state of compression.

4.1.9 Rolling Contact Fatigue

Rolling contact fatigue testing was performed at MRC (Jamestown, New York) using a ABEC

grade 5, 309–size deep groove ball bearing and at SBB (Timken Company, Canton, Ohio) using SBB part number 5HTH 207–D187, an angular contact ball bearing. All bearings were made from aircraft quality M50 steel. Each bearing vendor established a Weibull curve for an unplated (bare) M50 set of bearings to which the TDC plated bearings were compared. The TDC plated bearings passed the Rolling Contact Fatigue test if their L10 was greater than or equal to that of the unplated bearings with a 90% confidence.

4.2 Test Results

4.2.1 MRC Round No. 1

4.2.1.1 Thickness Checks

PASSED

The TDC thickness of 20 bearing inner and outer rings were checked using XRF. The lands, raceway, and faces of the inner rings were inspected as shown in Figure 2. Only the outer diameter and the faces of the outer rings were inspected as the part geometry would not allow the equipment to inspect the outer ring raceway. **Tables** 1 and 2 show the TDC thickness for the inner and outer rings, respectively. **Tables** 3 and 4 give the statistical results of the inner and outer ring thickness measurements. Note that the TDC readings all were within the specification of 40–100 µin, ranging from 45 to 93 µin in thickness. The bearing GE TDC 07 was subjected to extensive thickness checks with the results tabulated in **Table** 5. For this particular bearing, all the thickness data lies between 45 and 72 µin.

The thickness of the TDC coating was also checked as a function of subscale bearing endurance rolling contact fatigue operating time in four locations as shown in **Figure 2**, with the results being shown for GE TDC 27 in **Table** 6. It is evident from this data that the wear

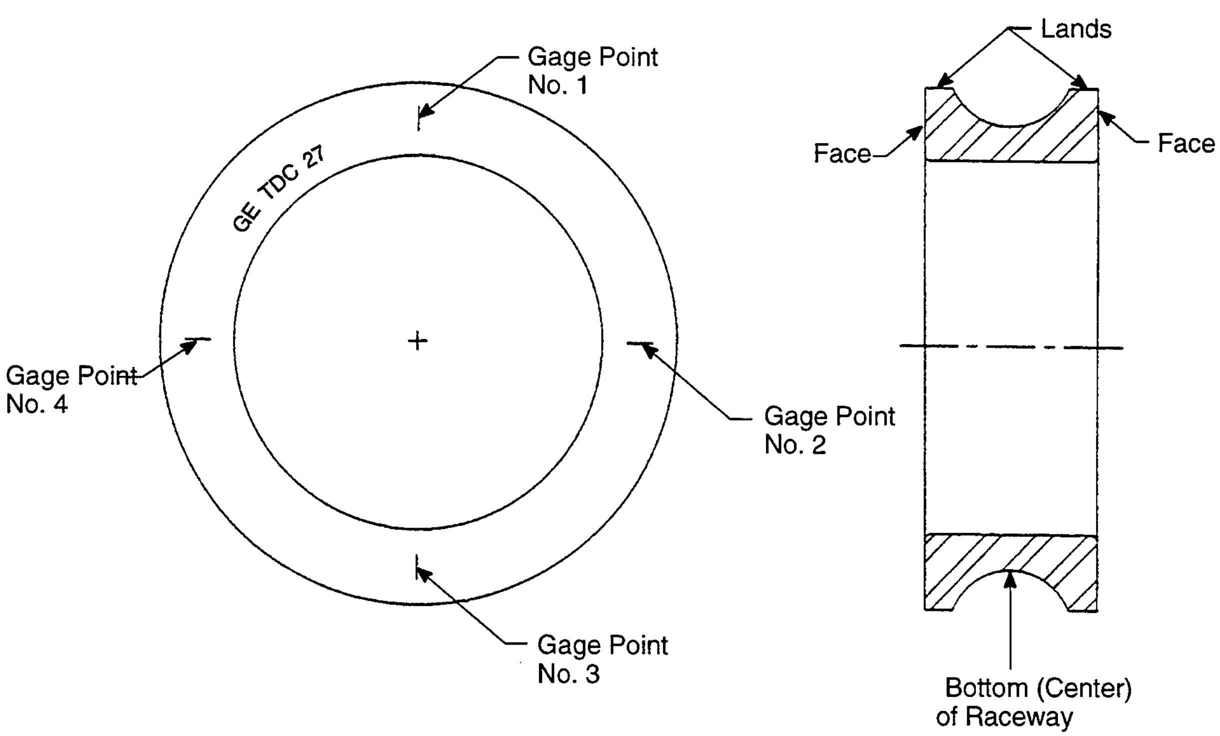


Figure 2. GE TDC 27 (MRC Round 1) Plating Thickness Measurement Locations.

Table 1. TDC Plating Thickness* on the Inner Rings (MRC Round 1).
All data is within the thickness specification.

Identification #	Land 1	Land 2	Loc 1	Loc 2	Face 1	Face 2
GE TDC 03	59	52	58	51	46	52
GE TDC 05	73	70	60	72	50	48
GE TDC 06	72	67	61	66	51	50
GE TDC 07	81	80	74	63	52	56
GE TDC 09	72	65	69	65	47	47
GE TDC 10	69	65	60	46	54	57
GE TDC 11	48	51	47	50	45	47
GE TDC 12	88	82	56	73	56	64
GE TDC 14	54	67	49	45	49	53
GE TDC 15	60	65	48	56	48	52
GE TDC 17	61	58	53	49	47	48
GE TDC 19	75	74	54	62	54	59
GE TDC 24	59	68	50	54	53	55
GE TDC 25	65	78	50	58	55	54
GE TDC 26	66	65	59	51	45	52
GE TDC 27	88	93	75	73	80	83
GE TDC 35	64	75	48	57	48	54
GE TDC 38	88	83	67	64	67	64
GE TDC 44	82	89	61	68	68	65
GE TDC 45	70	68	51	62	46	56

* plating thickness given in millionths of an inch

Table 2. TDC Plating Thickness* on the Outer Rings (MRC Round 1).
All data is within the thickness specification.

Identification #	Loc 1	Loc 2	Face 1	Face 2
GE TDC 03	60	65	67	59
GE TDC 05	78	69	56	70
GE TDC 06	86	88	64	80
GE TDC 07	74	74	66	69
GE TDC 09	68	65	58	56
GE TDC 10	71	77	76	68
GE TDC 11	78	70	58	63
GE TDC 12	68	65	48	55
GE TDC 14	75	68	58	51
GE TDC 15	78	88	84	71
GE TDC 17	70	65	58	70
GE TDC 19	79	81	71	77
GE TDC 24	80	70	60	68
GE TDC 25	90	93	75	85
GE TDC 26	52	52	52	50
GE TDC 27	76	75	60	83
GE TDC 35	70	74	72	60
GE TDC 38	80	77	65	60
GE TDC 44	72	72	69	72
GE TDC 45	70	72	56	58

* plating thickness given in millionths of an inch

Table 3. Summary Statistics of TDC Plating Thickness on the Inner Rings (MRC Round 1 Data Table 1). *All data is within the specification, with variation as large as 45 μin.*

Parameter	Land	Raceway	Face
Mean	70.2	58.4	54.4
Std dev	11.2	8.7	N/A
Min	48	45	45
Max	93	75	83
Range	45	30	38

Table 4. Summary Statistics of TDC Plating Thickness on the Outer Rings (MRC Round 1, Data Table 2). *All data is within the specification, with variation as large as 41 μin.*

Parameter	OD	Face
Mean	73.4	65.0
Std dev	8.9	9.6
Min	52	48
Max	93	85
Range	41	37

Table 5. Detailed Thickness Measurements* on Inner Ring GE TDC 07 (MRC Round 1). *All data is within the thickness specification.*

Placement	0°	120°	240°
Marking-side Land†	68	61	70
	67	59	70
	69	57	67
Plain-side Land†	63	66	67
	65	63	70
	64	63	71
Bottom of Raceway†	68	66	58
	71	61	54
	72	64	55
Bore‡	55	55	70
	50	60	65
	55	55	70
Marking-side Face†	45	47	56
	49	43	55
	47	49	54
Plain-side Face†	51	47	55
	47	50	53
	50	47	56

* Thickness measurements in millionths of an inch
† Measured by X-ray Fluorescence
‡ Measured by the Kocour Test

Table 6. GE TDC 27 (MRC Round 1) Plating Thickness* Measurements Versus Actual Testing Times. *Note minimal thickness reduction as a function of running time.*

Hours	Location #1	Location #2	Location #3	Location #4
100	68	70	77	77
500	67	71	76	74
1000	64	69	66	61
1500	62	68	67	61
1729.5	59	66	68	60

* plating thickness given in millionths of an inch

rate of the TDC coating for this particular application is quite slow, even at the high contact stresses (475 ksi) used in the rolling contact fatigue portion of this testing. This particular bearing failed after 1,729 hours, so data is not available out to the 2,500–hour suspension time.

4.2.1.2 Topography

PASSED

Figures 3 through 10 show the TDC topography of the raceway and shoulder in four different locations around the bearing using the scanning electron microscope (SEM) at 500X. The coating exhibits a nodular TDC without any evidence of cracking. Although this topography passed the GE specification, some variation in nodule size is evident in these micrographs.

4.2.1.3 Corrosion Testing

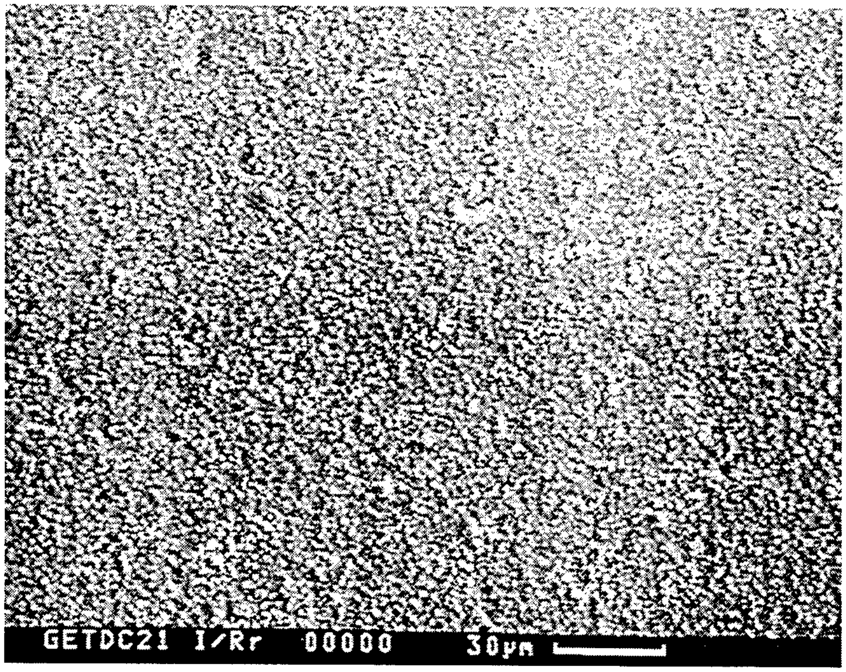
PASSED

The tested bearing is shown in **Figure** 11. The staining which is evident on the bearing came from stamp marks, vibration peen marks, and corners of the sample, and was not present in the ball track. It was estimated that the total corrosion was less than 1% of the total area and most of the poor appearance was due to runoff from those isolated areas. A certification of the testing results is included in Appendix A. Although the sample was deemed to have passed this 24–hour salt spray test, the evidence of corrosion indicated that making a bearing totally free from localized corrosion may be difficult and achieving an absolute corrosion free part after the 24–hour salt spray exposure is very challenging.

4.2.1.4 Hydrogen Embrittlement

PASSED

Hydrogen embrittlement testing was performed using the specimen as shown in **Figure** 12. Six plated specimens were all able to withstand a load equal to 75% of the average notch tensile strength for a period of 200 hours. This indicates that the baking cycle was effective in eliminating or significantly reducing any embrittlement which may have been introduced during the plating process. Certification of the test results are in Appendix A.



500X

Figure 3. SEM Quality/Topography Photo of Position 1 (0°) in Raceway. *Within spec.*

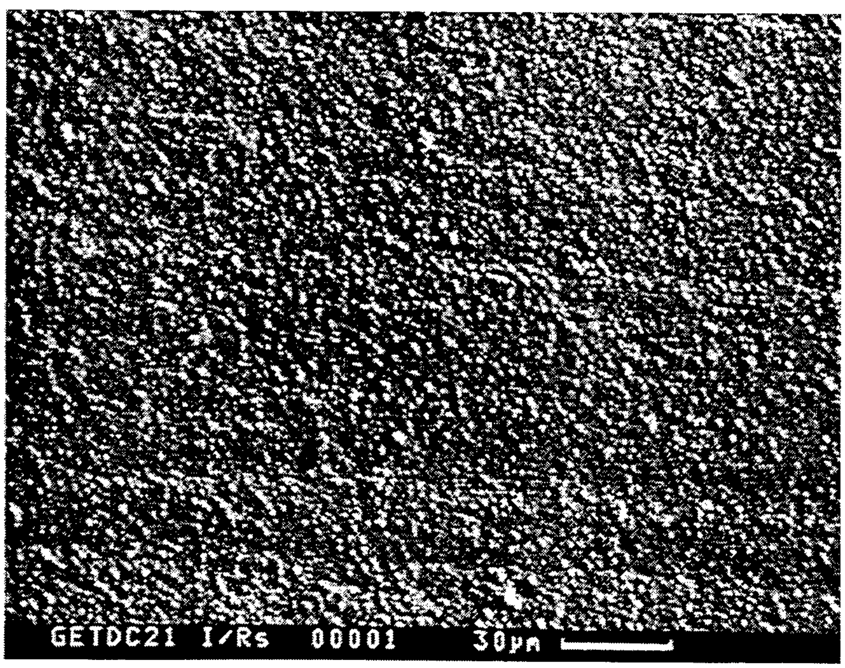


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Figure 4. SEM Quality/Topography Photo of Position 1 (0°) in Shoulder. *Within spec.*

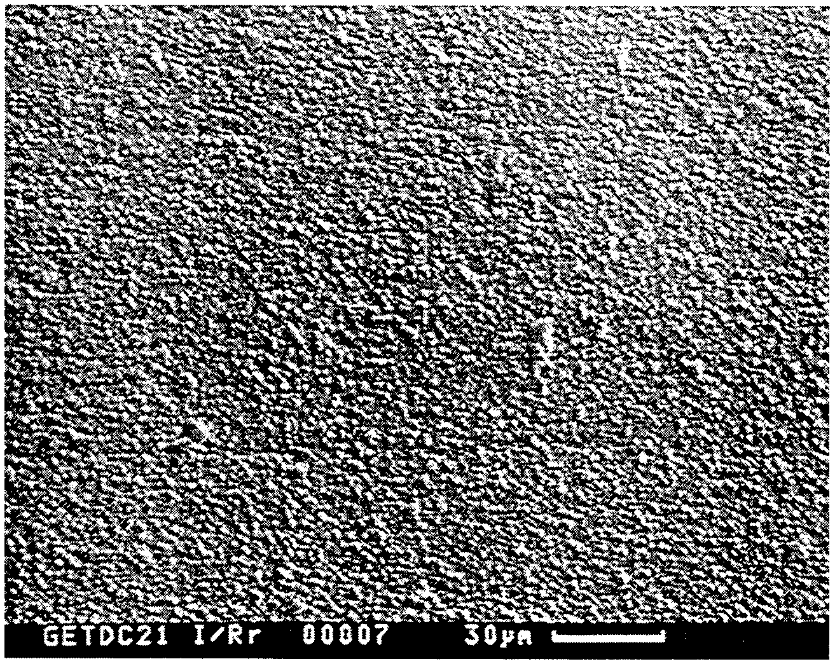

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Figure 5. SEM Quality/Topography Photo of Position 2 (90°) in Raceway. *Within spec.*

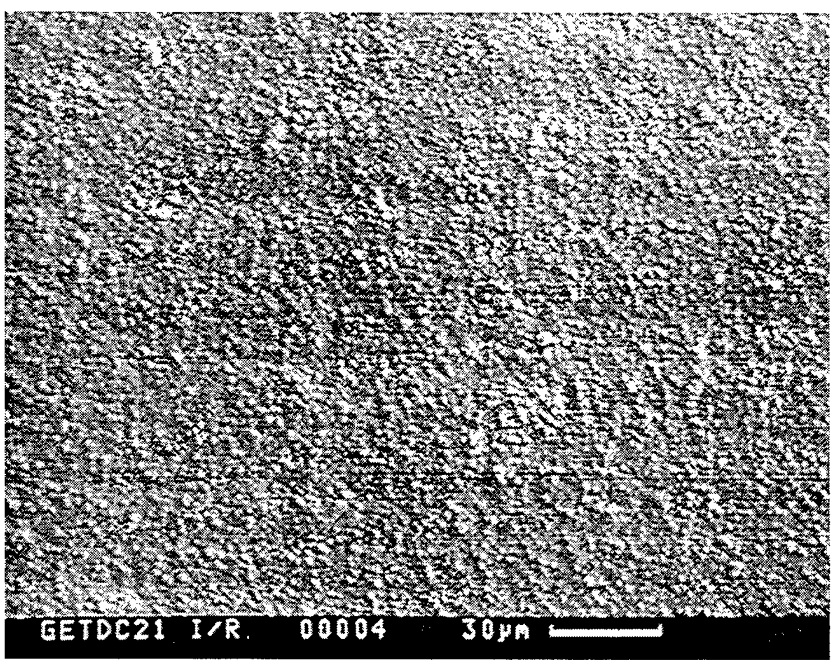

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Figure 6. SEM Quality/Topography Photo of Position 2 (90°) in Shoulder. *Within spec.*

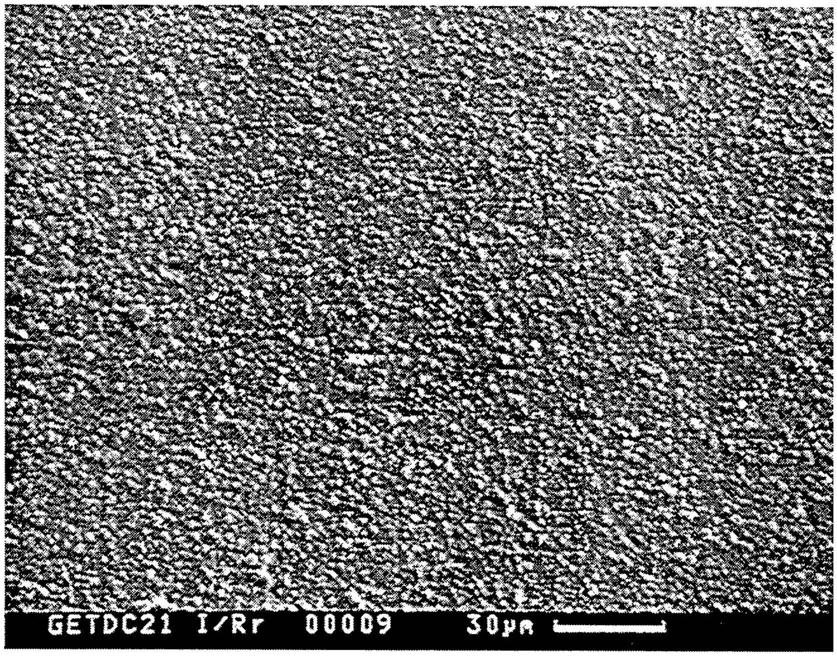

Figure 7. SEM Quality/Topography Photo of Position 3 (180°) in Raceway. *Within spec.*

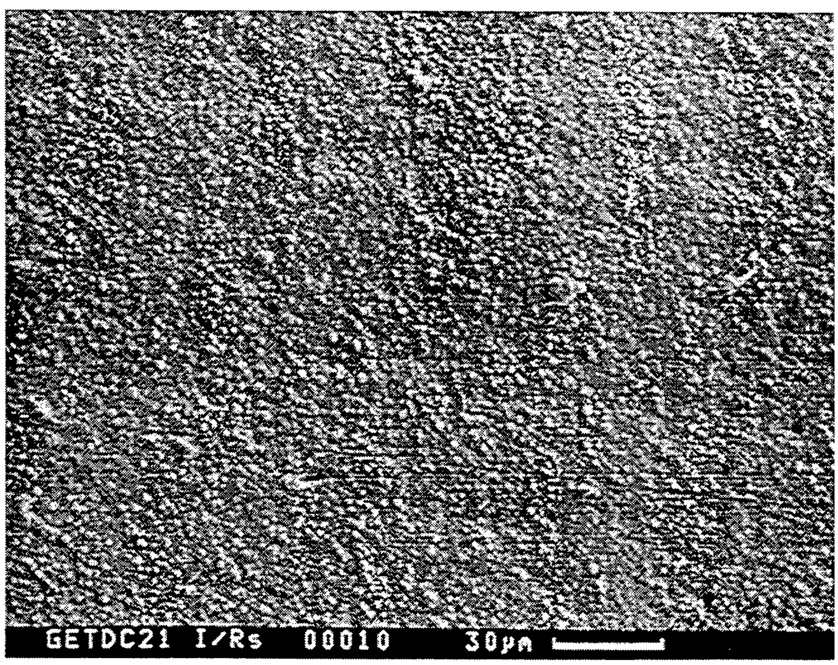

Figure 8. SEM Quality/Topography Photo of Position 3 (180°) in Shoulder. *Within spec.*

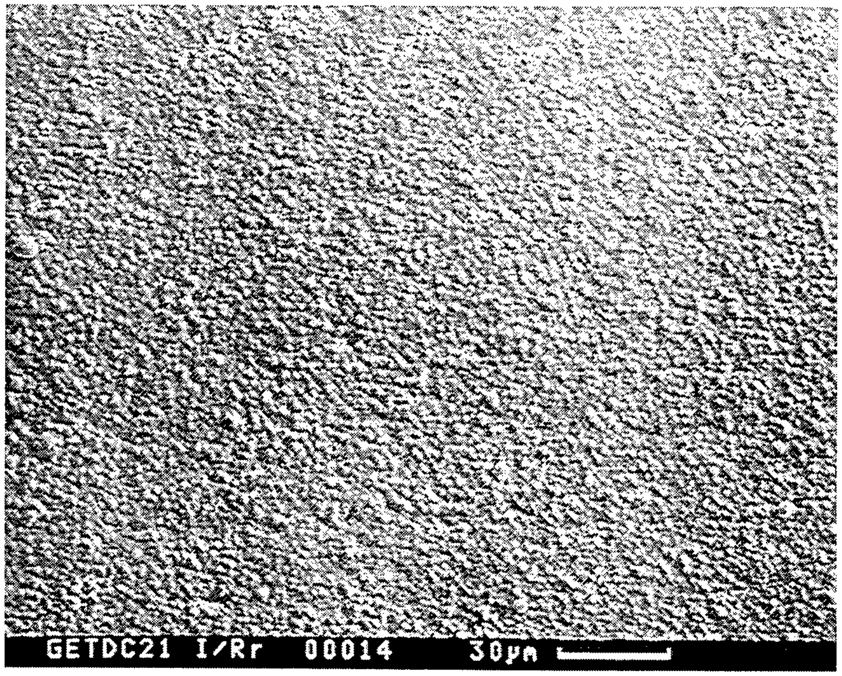

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Figure 9. SEM Quality/Topography Photo of Position 4 (270°) in Raceway. *Within spec.*

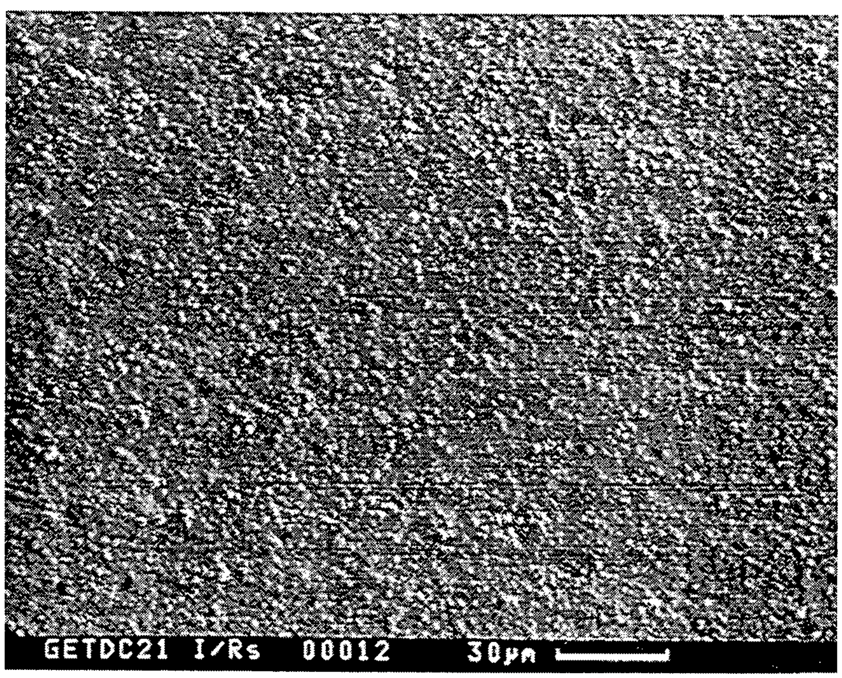

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Figure 10. SEM Quality/Topography Photo of Position 4 (270°) in Shoulder. *Within spec.*

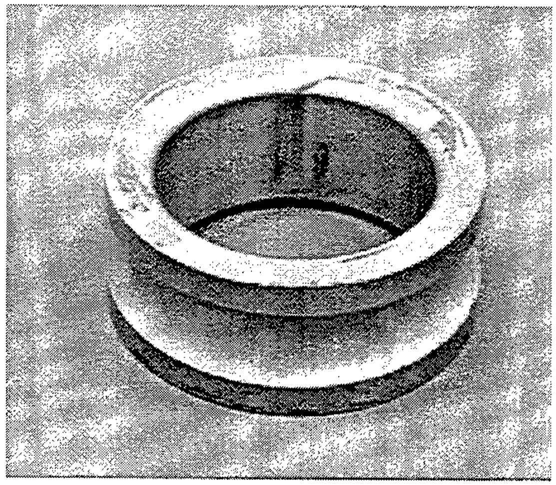


Figure 11. Photo of Inner Ring from 24–Hour Salt Spray Test (MRC Round 1). *Although the ball track was free of corrosion, a few isolated areas did corrode resulting in the staining evident in the photo.*

4.2.1.5 Wear Testing

PASSED

Taber wear data indicates a wear index of 0.2 (an average of 1.0 milligram weight loss) for the three specimens tested. This is considerably less than the requirement of a wear index 1.2 or less. **Figure** 13 shows a typical posttest specimen. The test machine used was at Bridgeport Testing Laboratory. The test certification is included in Appendix A.

4.2.1.6 Adhesion Testing

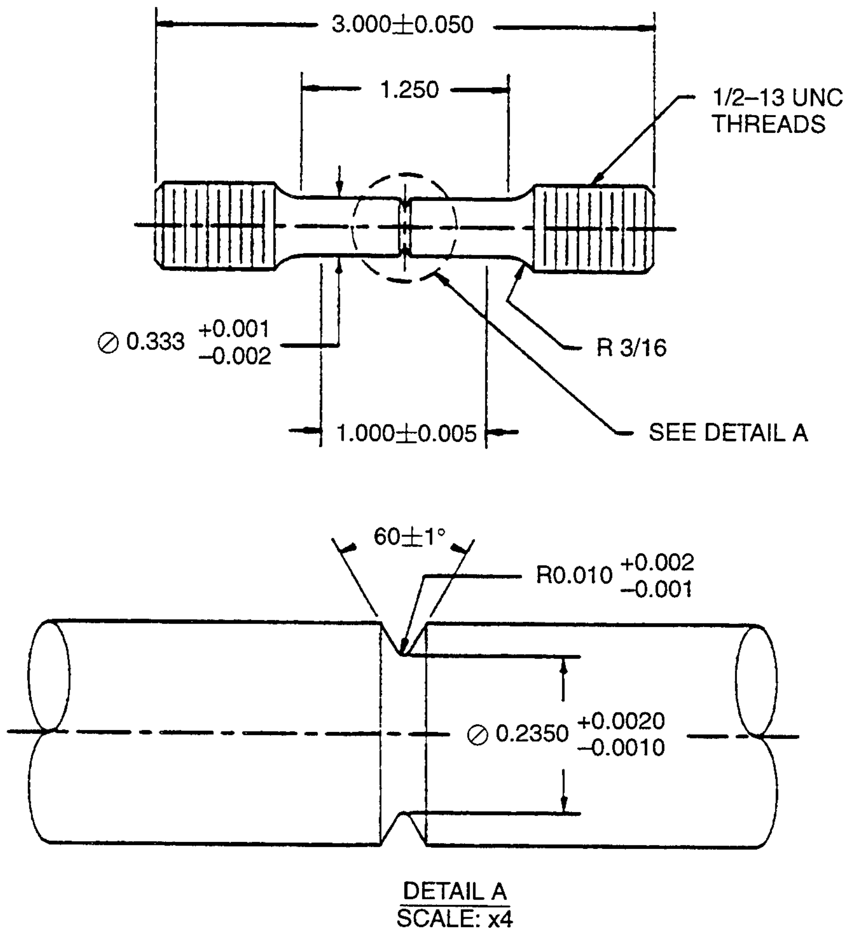
PASSED

Figure 14 shows the panel used in the bend test performed by Armoloy of Connecticut. Postbend test inspection indicated that the TDC coating adhered to the base metal, and did not flake, peel, or delaminate.

4.2.1.7 Thermal Shock Testing

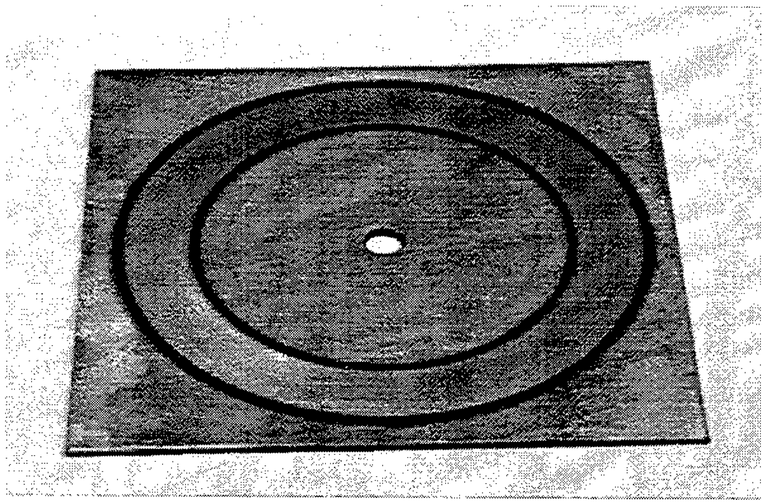
PASSED

Postthermal shock inspection showed no evidence of cracking or peeling of the TDC, although a few small discrete areas of staining (discoloration) were evident. The discoloration or staining was probably caused by water condensation on the bearing. In particular, in any pits or cracks in the TDC coating in the few areas noted. This condensation in turn likely caused a small amount of corrosion in those few areas which appear as staining or discoloration upon visual inspection. **Figures** 15 through 18 show the test specimen with attached thermal couple leads, in the quench chamber, liquid nitrogen tank and data acquisition system, and in the oven used throughout this testing. **Figure** 19 shows the temperature profile traces of the 10 thermal cycles used in this experiment. **Figures** 20 through 35 show the TDC surface postthermal shock for the two bearing rings used in this evaluation. The TDC appears to be generally free of any cracking or delamination and appears to be in good condition at all positions.



Note: Root radii, reduced section, and notch root radius must be consentric with centerline of specimen within 0.003 T.I.R. Transitional taper to blend and fair into the 0.009/0.012 in (0.02/0.30 mm) radius. All surfaces of the notch must have a 32 finish.

Figure 12. Specimen Geometry for the Hydrogen Embrittlement Test.



0.7X

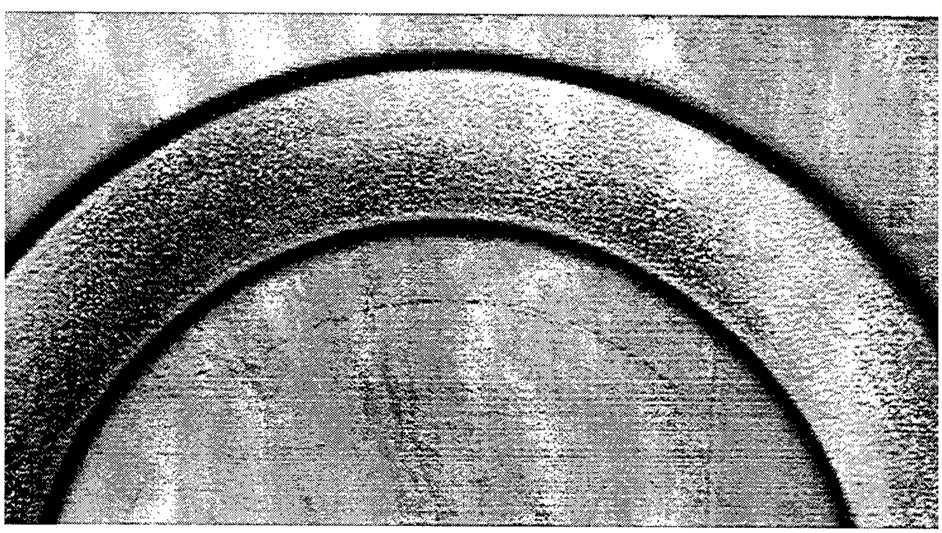


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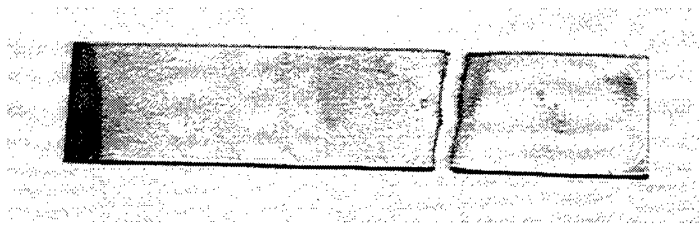
Figure 13. Photos of Taber Wear Test Specimen.
Specimen wear of 0.2 was well below the upper wear index limit of 1.2.



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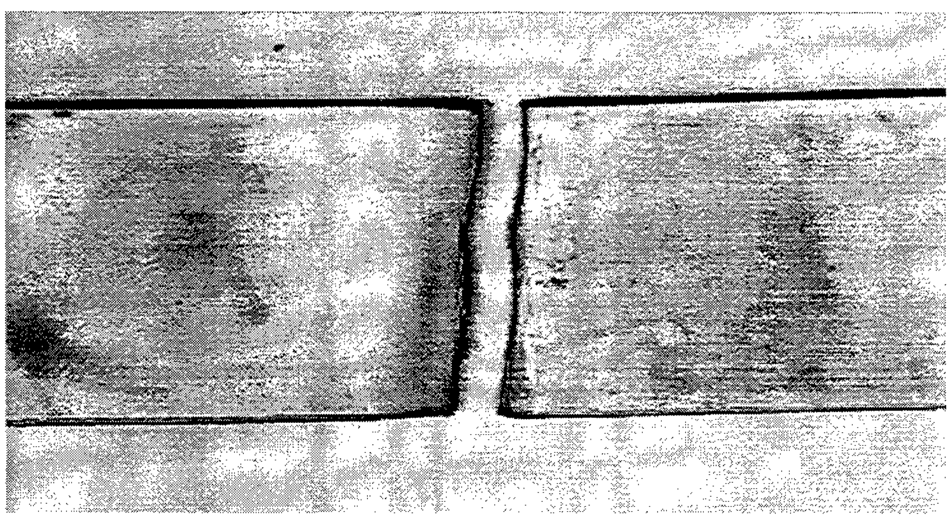

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Figure 14. Photos of Bend Test Specimen.
TDC did not flake, peel, or delaminate.

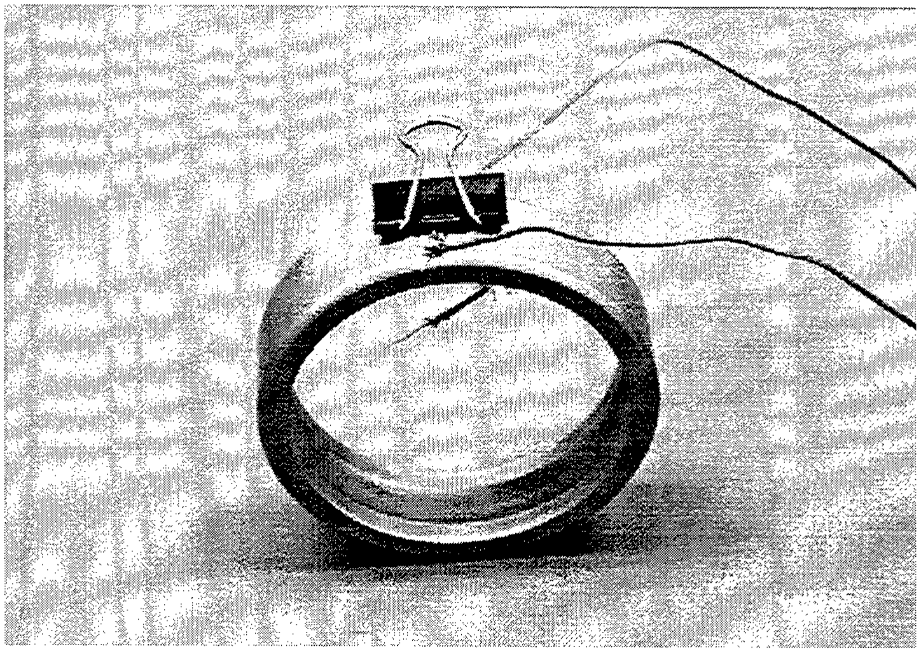

Figure 15. Photo of Bearing Outer Race Used in Thermal Shock Test.
Thermocouples were used to monitor test temperature.

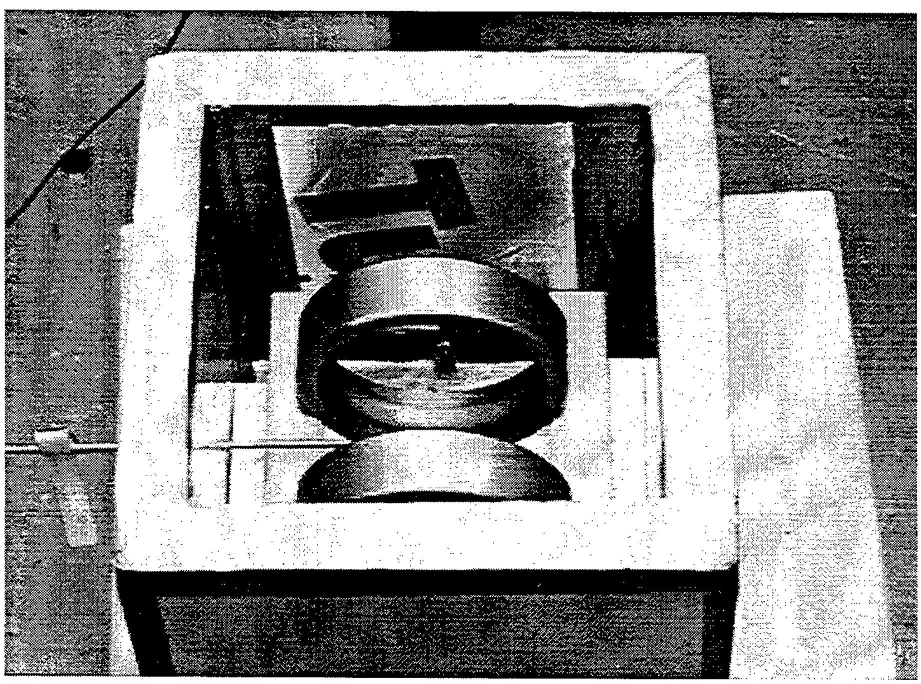

Figure 16. Photo of Quench Chamber Used in Thermal Shock Test.

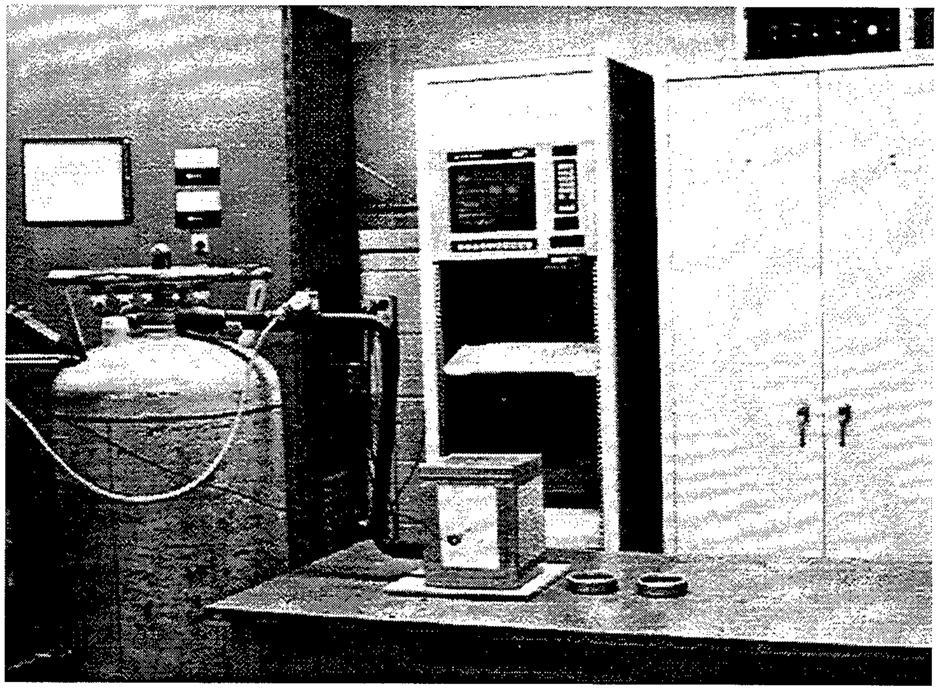

Figure 17. Photo of Thermal Shock Test Equipment Setup.
Liquid nitrogen tank is piped to quench chamber (foreground) and data acquisition system shown (background).

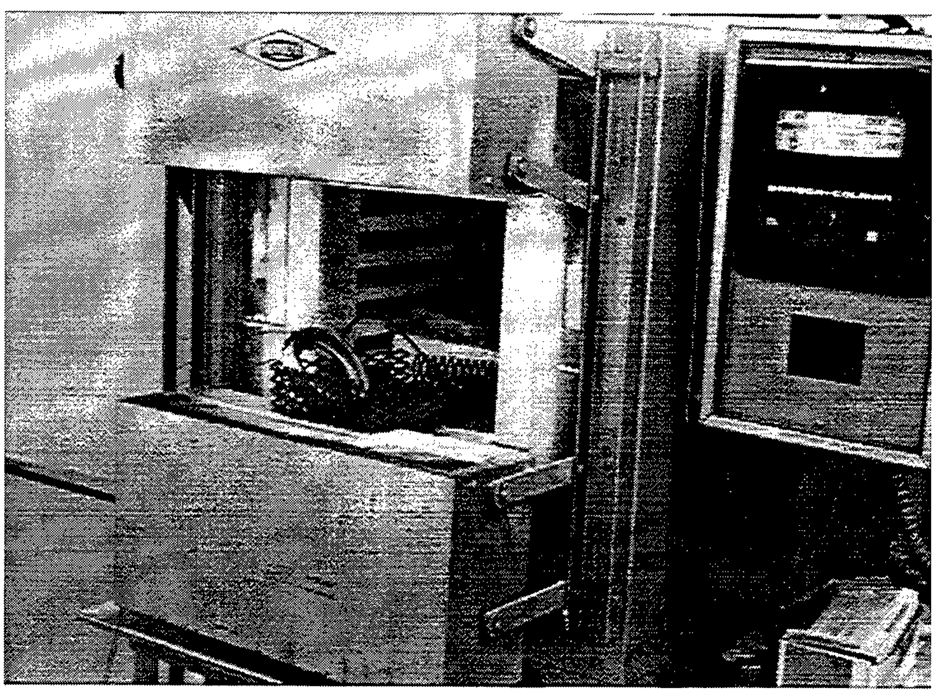

Figure 18. Photo of Bearing and Oven Used in Thermal Shock Test.

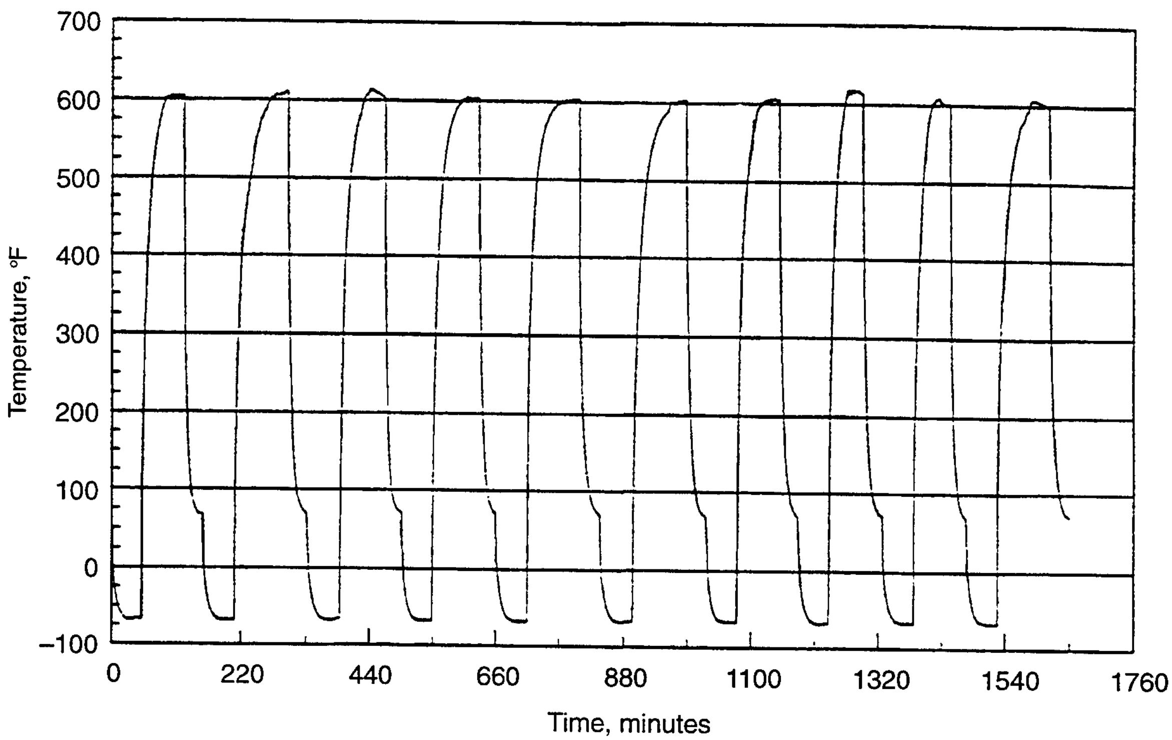

Figure 19. Plot of Thermal Shock Ring Temperatures.
Temperatures cycle from –65°F to +600°F.

4.2.1.8 Residual Stress

PASSED

Residual stress measurements performed on the surface of the raceway and face of an inner ring demonstrated that the TDC coating was in a state of residual compressive stress as required by the GE specification. **Table** 7 shows the before–plate and after–plate residual stresses of the sample bearing. Although there was a change in the magnitude of residual stress from the plating operation, it was still compressive in nature. In addition to the as–plated residual stress measurements, MRC measured residual stresses on TDC and nonTDC–coated bearings before and after running at 475 ksi for 2,500 hours. The locations in the race where the measurements were made are shown in Figure 36. This is the same location where contact stresses were applied. The results of the residual stress measurements are shown in **Table** 8 and Figures 37 and 38. After running the surface was still in a state of residual compressive stress, which is desirable. Also evident from this data, the TDC coated bearings residual stress profile appeared to have been altered deeper than that of the plain M50 bearing. It should be noted that when performing residual stress measurements on homogeneous materials it is more relevant to look at trends rather than absolute numbers.

4.2.1.9 Rolling Contact Fatigue

FAILED

Figure 39 shows the ABEC 5, 309–size ring dimensions of the bearings used in the rolling contact fatigue endurance testing portion of this round of testing. This bearing is a 45mm deep groove ball bearing which was tested by running under a radial load. The material used to make these components was aircraft quality M50 steel. Five groups of four bearings for both the baseline (unplated) and the TDC plated

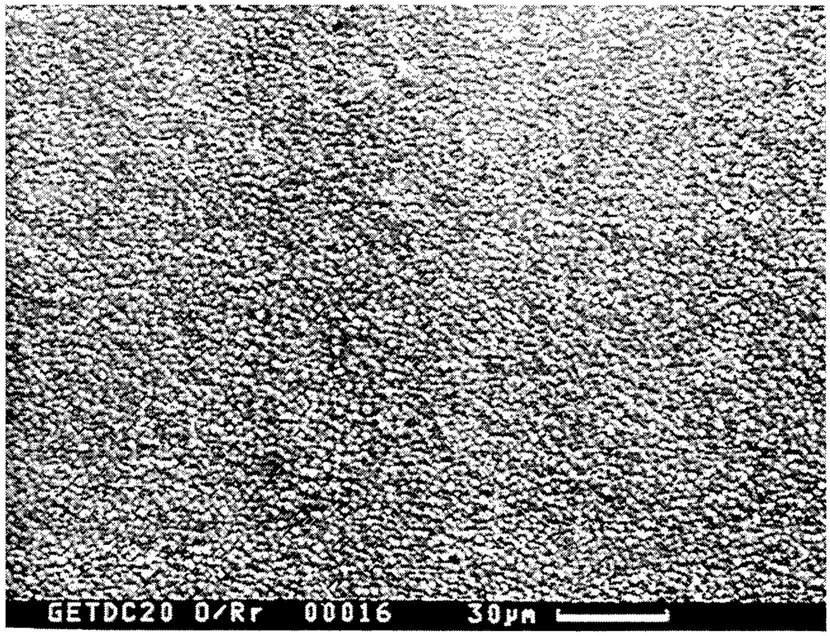

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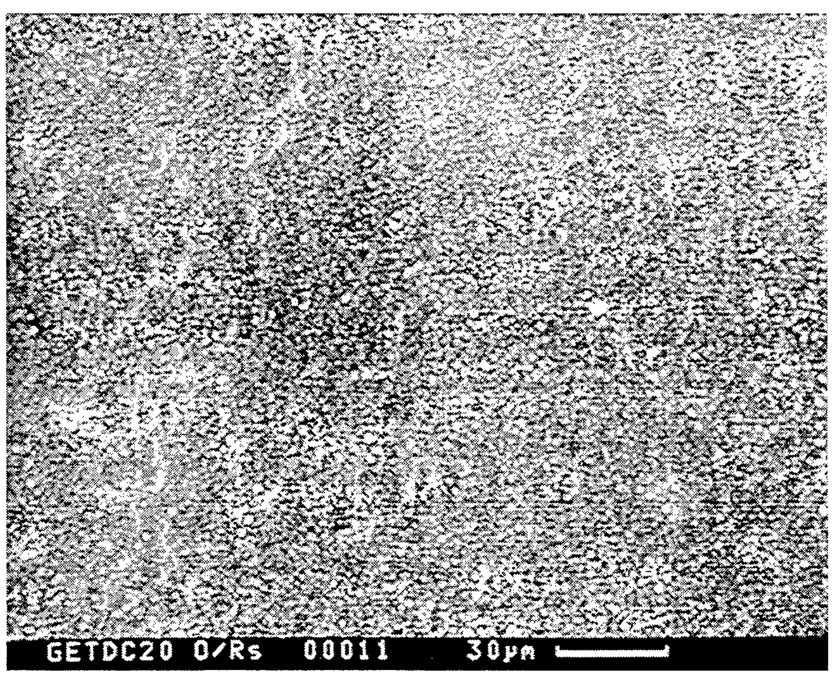
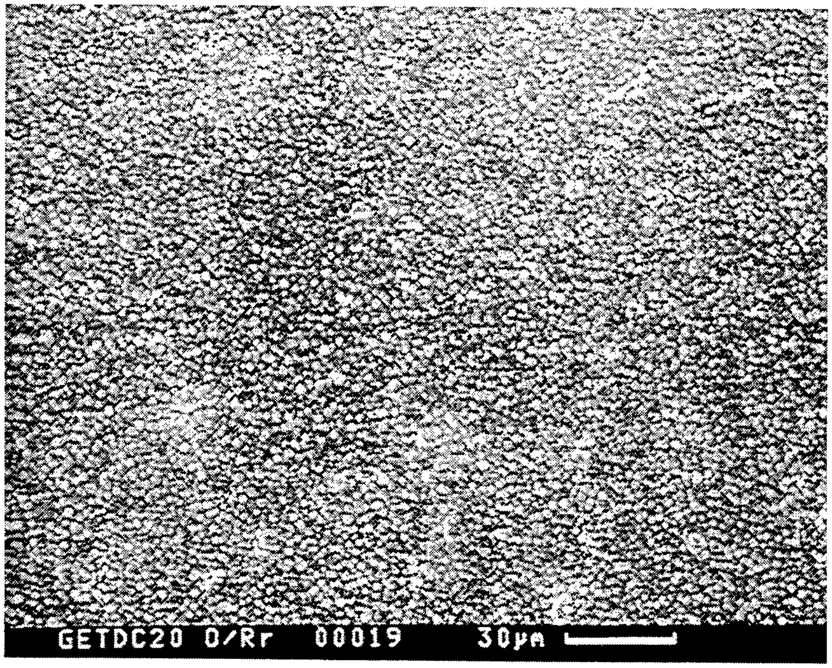
Figure 20. Thermal Shock Specimen GE TDC 20 SEM Photo of Position 1 (0°) in Raceway (MRC Round 1). *TDC is in good condition.*



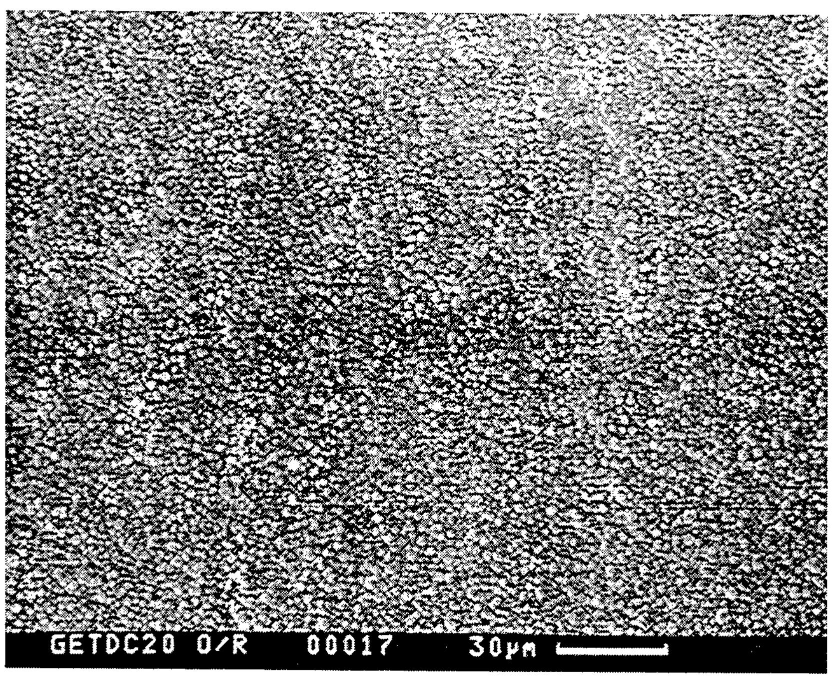
500X

Figure 21. Thermal Shock Specimen GE TDC 20 SEM Photo of Position 1 (0°) in Shoulder (MRC Round 1). *TDC is in good condition.*



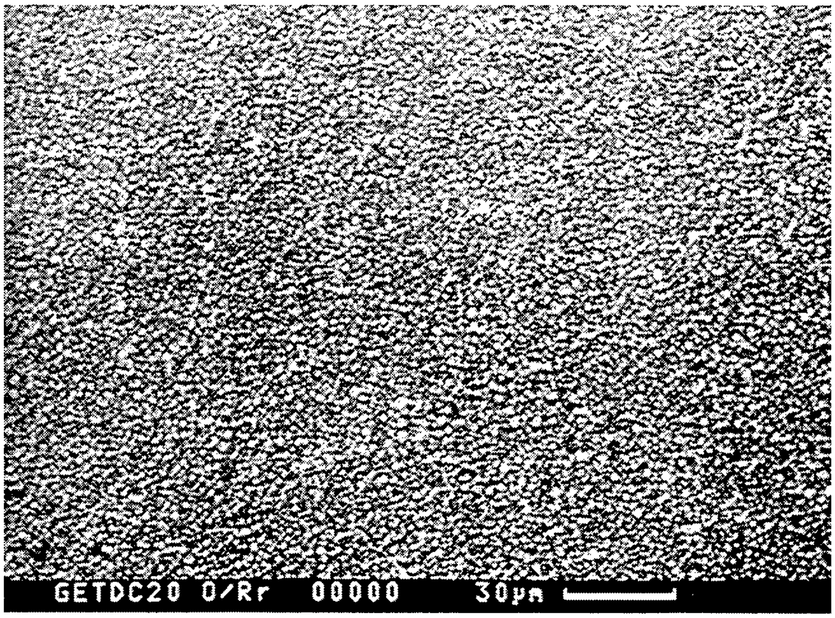
500X

Figure 22. Thermal Shock Specimen GE TDC 20 SEM Photo of Position 2 (90°) in Raceway (MRC Round 1). *TDC is in good condition.*



500X

Figure 23. Thermal Shock Specimen GE TDC 20 SEM Photo of Position 2 (90°) in Shoulder (MRC Round 1). *TDC is in good condition.*



500X

Figure 24. Thermal Shock Specimen GE TDC 20 SEM Photo of Position 3 (180°) in Raceway (MRC Round 1). *TDC is in good condition.*

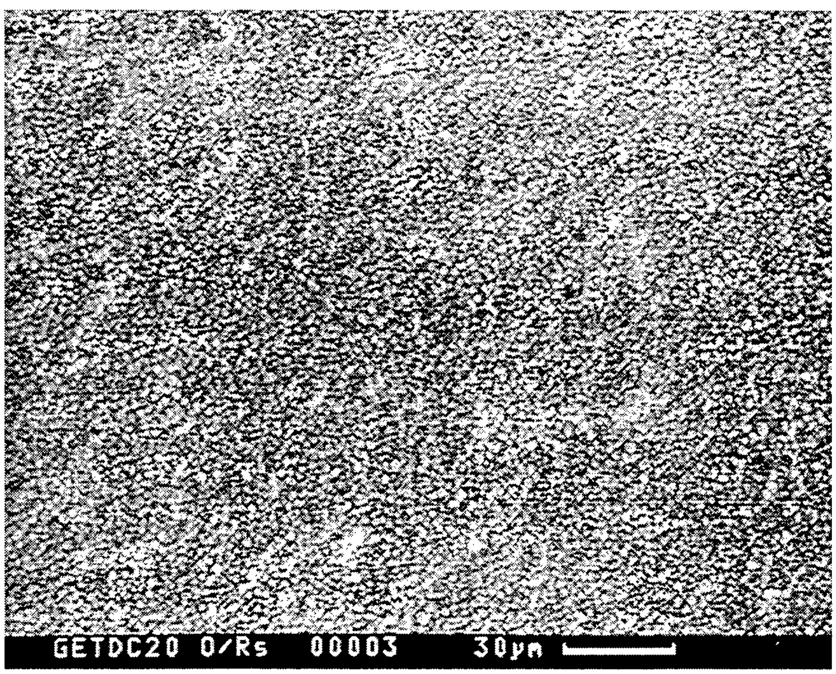


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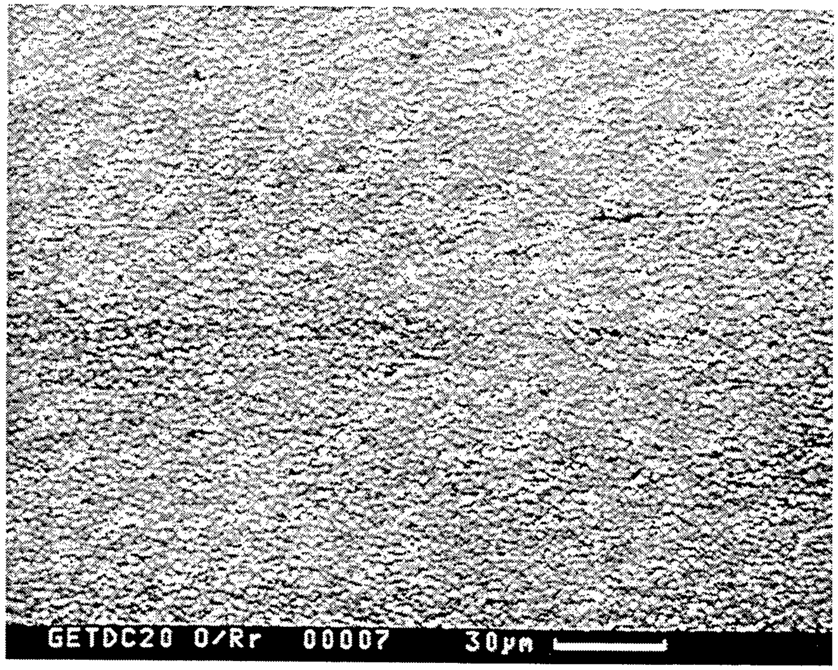
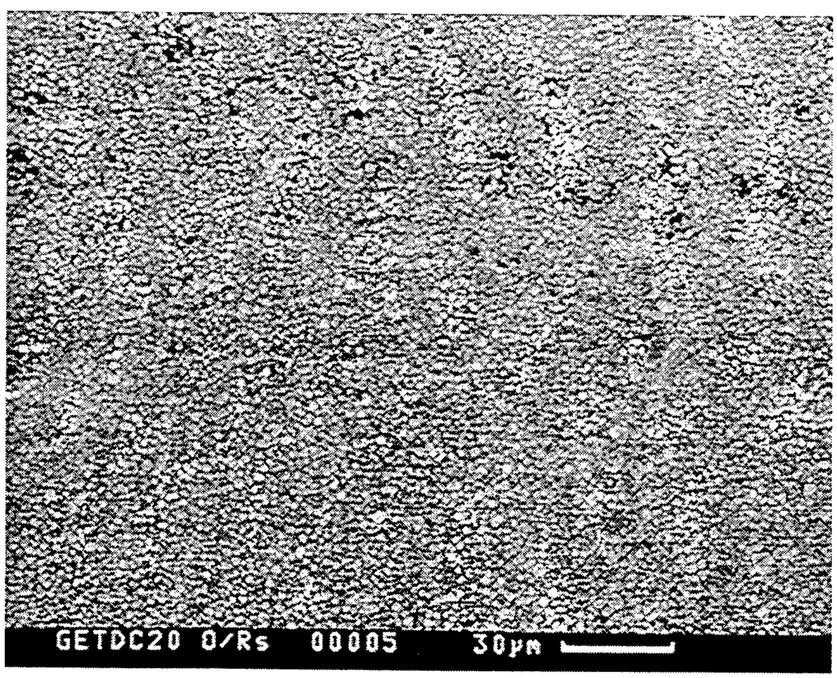
Figure 25. Thermal Shock Specimen GE TDC 20 SEM Photo of Position 3 (180°) in Shoulder (MRC Round 1). *TDC is in good condition.*



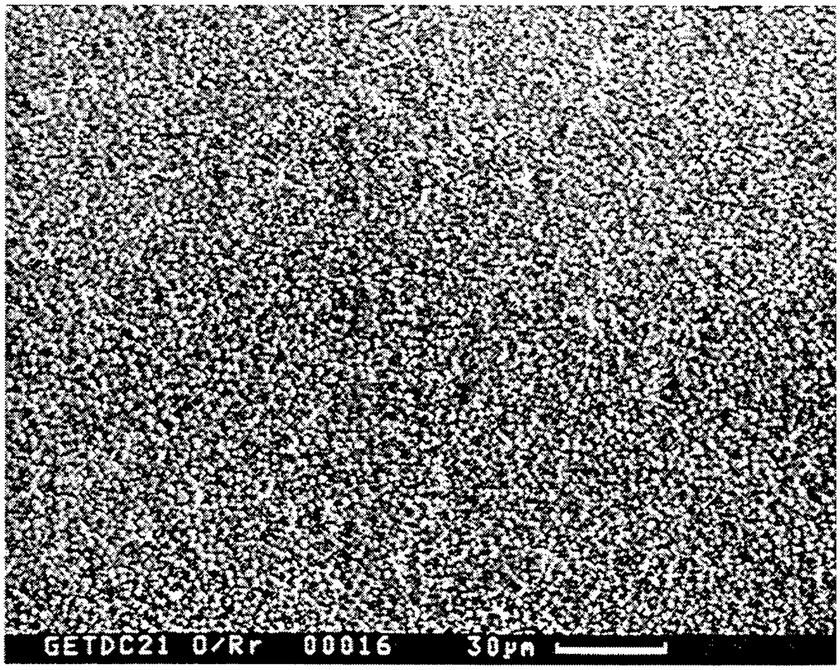
500X

Figure 26. **Thermal Shock Specimen GE TDC 20 SEM Photo of Position 4 (270°) in Raceway (MRC Round 1).** *TDC is in good condition.*



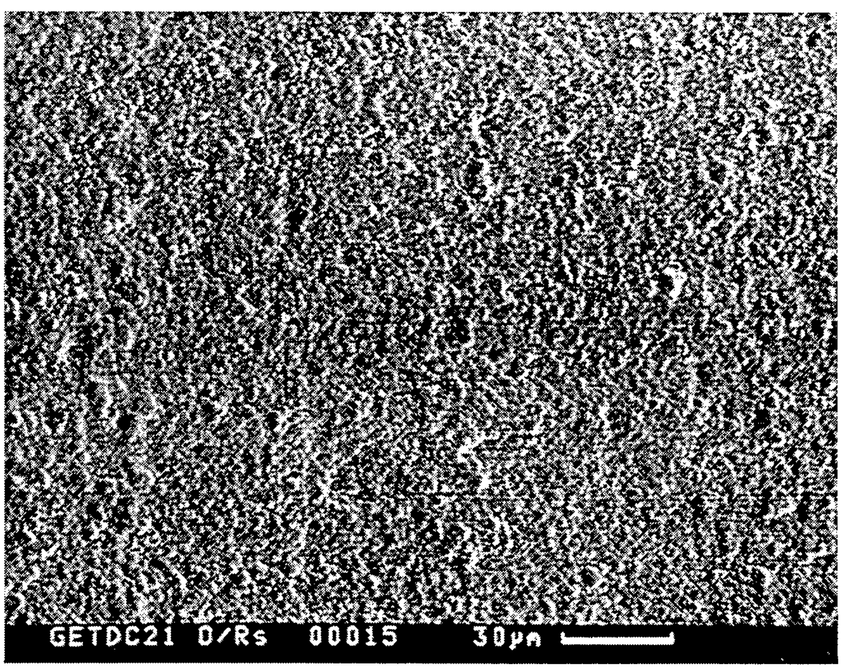
500X

Figure 27. **Thermal Shock Specimen GE TDC 20 SEM Photo of Position 4 (270°) in Shoulder (MRC Round 1).** *TDC is in good condition.*



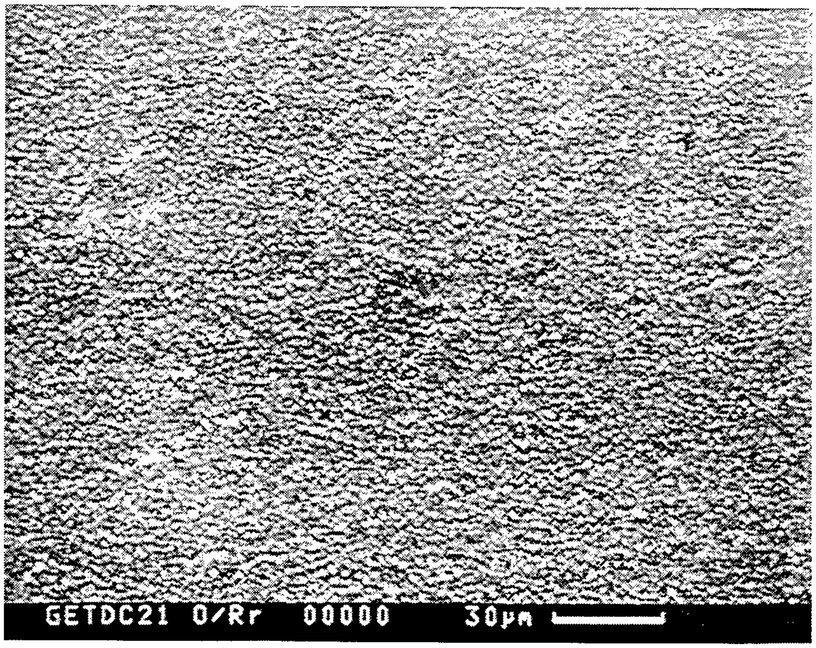
500X

Figure 28. **Thermal Shock Specimen GE TDC 21 SEM Photo of Position 1 (0°) in Raceway (MRC Round 1).** *TDC is in good condition.*



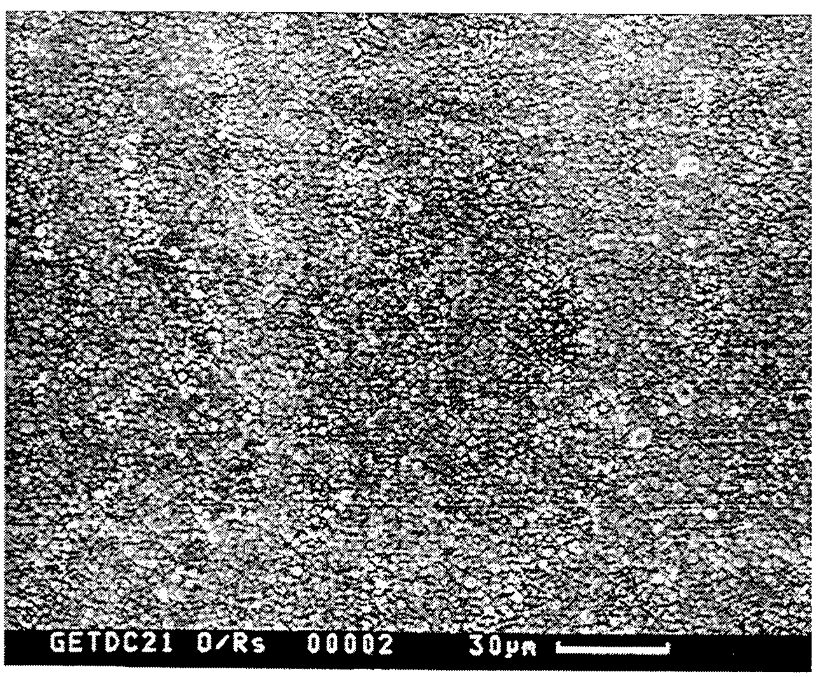
500X

Figure 29. **Thermal Shock Specimen GE TDC 21 SEM Photo of Position 1 (0°) in Shoulder (MRC Round 1).** *TDC is in good condition.*



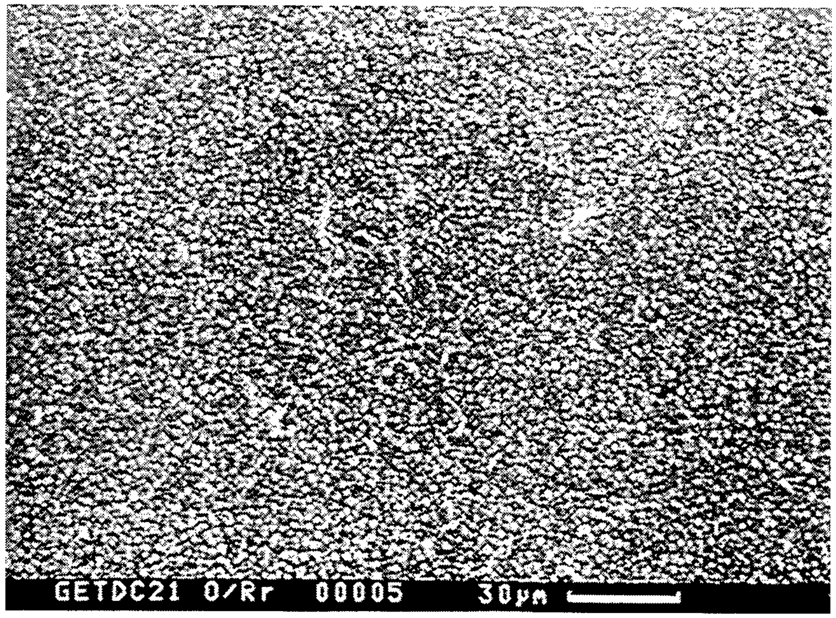
500X

Figure 30. Thermal Shock Specimen GE TDC 21 SEM Photo of Position 2 (90°) in Raceway (MRC Round 1). *TDC is in good condition.*



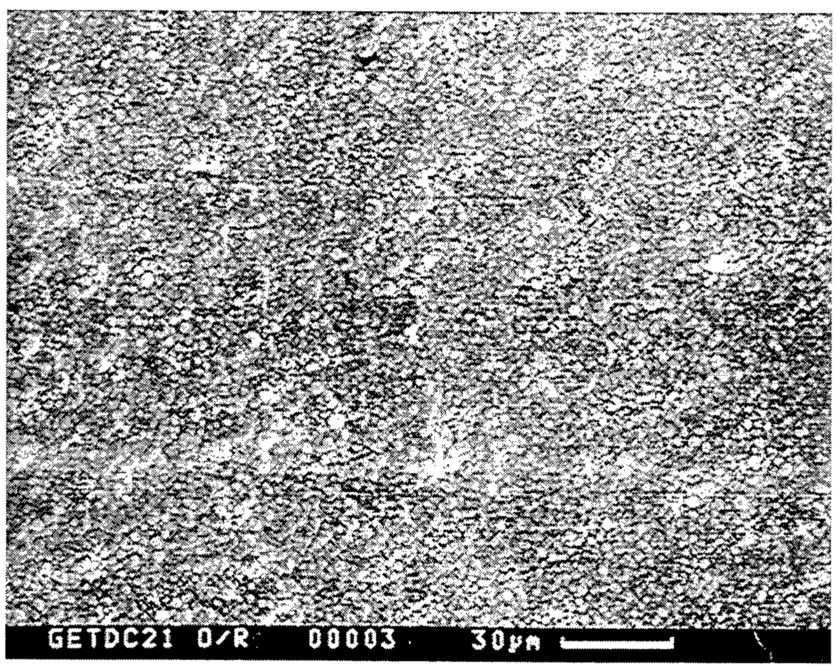
500X

Figure 31. Thermal Shock Specimen GE TDC 21 SEM Photo of Position 2 (90°) in Shoulder (MRC Round 1). *TDC is in good condition.*



500X

Figure 32. Thermal Shock Specimen GE TDC 21 SEM Photo of Position 3 (180°) in Raceway (MRC Round 1). *TDC is in good condition.*



500X

Figure 33. Thermal Shock Specimen GE TDC 21 SEM Photo of Position 3 (180°) in Shoulder (MRC Round 1). *TDC is in good condition.*

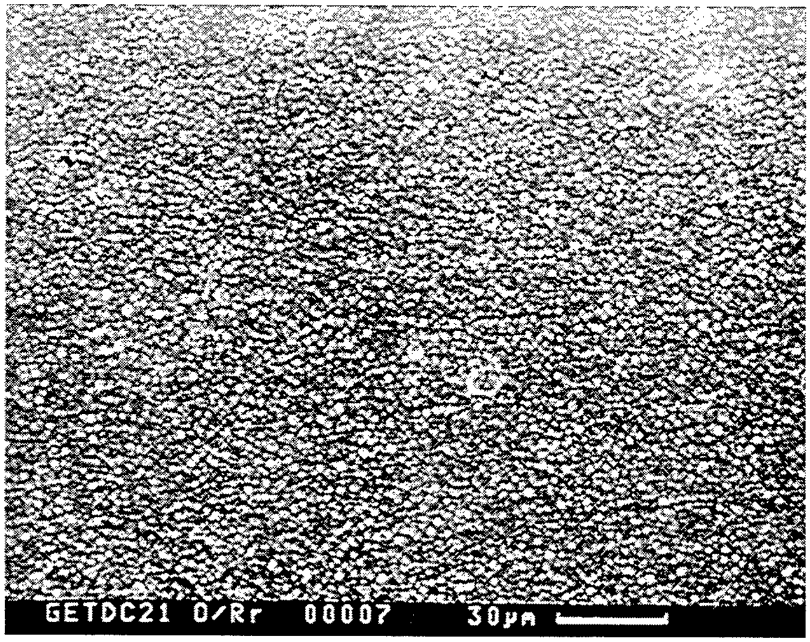


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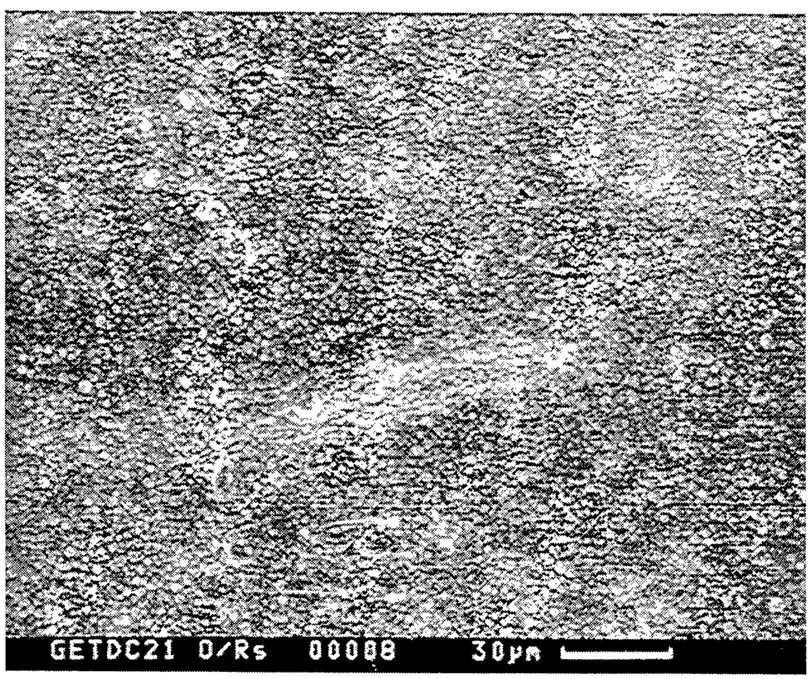
Figure 34. Thermal Shock Specimen GE TDC 21 SEM Photo of Position 4 (270°) in Raceway (MRC Round 1). *TDC is in good condition.*



500X

Figure 35. Thermal Shock Specimen GE TDC 21 SEM Photo of Position 4 (270°) in Shoulder (MRC Round 1). *TDC is in good condition.*

Table 7. Residual Stress Measurements at the Surface of a 9124 (2B) Inner Ring, ksi (MRC Round 1). *Data shows TDC plate is in a compressive state as specified.*

	Before Plate		After plate		Change	
	0°	180°	0°	180°	0°	180°
Face	-212.7	-204.8	-158.9	-145.2	53.8	59.6
Race	-145.3	-126.2	-106.2	-105.2	39.1	21.0

bearings were run at a contact stress of 475 ksi, a speed of 6,000 RPM, using MiL–L–7808 oil with an oil in temperature of approximately 160°F on the MRC "G" machines as shown in **Figure** 40. When one of the four bearings in each respective group failed, the remaining bearings in that group were considered suspended, Sudden Death Method. Tables 9 and 10 include the results of that testing.

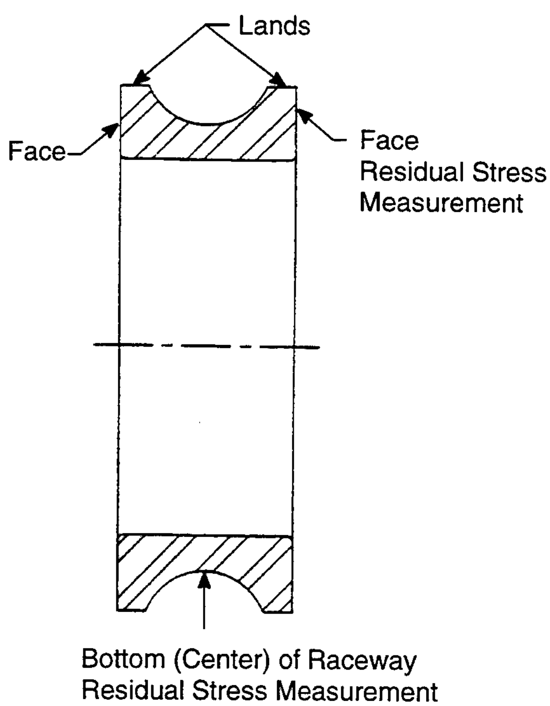


Figure 36. Residual Stress Measurement Locations.

In all, one baseline bearing failed (S/N 32) at 250 hours and three TDC coated bearings failed (S/N 45 at 802 hours, S/N 9 at 876 hours, and S/N 24 at 2,152 hours). The resulting Weibull L10 lives were 6,475 hours for the baseline bearings and 1,178 hours for the TDC coated bearings. Statistical analysis indicated with 90% certainty that the TDC bearing fatigue lives were inferior to the baseline for this particular set of testing. **Figures** 41 through 44 show the fatigue spalls from the one baseline and three TDC coated fatigue failures. Surface initiated failures are often characterized by a point origin from which the spall grows. The spall itself often has a low entrance angle. Subsurface spalls on the other hand have rounded or blunted leading edges and a steep entrance angle. Additionally, subsurface spalls often run deeper than surface spalls. Figure 44 shows a dent at the leading edge of the spall on GE TDC 45. This failure was characterized as being surface originated. Of the three TDC coated bearing failures, two failed from subsurface fatigue and one from what appeared to be surface initiated fatigue. The baseline uncoated bearing failed from what appeared to be subsurface initiated fatigue.

An examination of the failed TDC plated bearings revealed a 360° contact path on most of the outer rings, as shown in **Figure** 45, instead of the typical pattern in which the nonloaded half shows essentially no ball path. Although it was

Table 8. **Residual Stress Profile Results of Baseline and TDC Bearing Inner Rings, ksi (MRC Round 1).** *Note increase in compressive stress, particularly for TDC coated bearing after 2500 hours of running.*

Depth	S/N 97 (Baseline, unrun)	S/N 02 (Baseline, 2500 hours)	GE TDC 21 (TDC, unrun)	GE TDC 06 (TDC, 2500 hours)
Surface	-119.0	-90.3	-88.8	-141.7
.0002	-15.2	-57.1	-67.8	-93.8
.0004	-1.6	-41.8	-41.4	-64.1
.0006	-6.0	-45.5	-25.2	-41.6
.0008	-8.3	-53.4	-20.6	-37.5
.0010	-18.0	-48.4	1.0	-39.1
.0020	0.5	-59.6	36.4	-25.0
.0030	-7.0	-33.1	8.1	-30.7
.0040	-21.3	-21.6	2.5	-33.1
.0050	-5.7	-39.0	1.3	-52.4
.0100	-1.7	-33.9	10.5	-117.2
.0150	-6.4	-27.5	15.3	-85.8
.0200	-4.5	-15.1	5.4	-20.3

difficult to visually see any ball path in the plain bearings, and nearly impossible to photograph it, comparisons made to the TDC plated bearings indicated that the TDC ball paths, which were easy to see, were approximately 10–20% wider; evidence that the TDC plated bearings operated at a higher load or higher temperature.

An examination of the M50 balls from both the TDC plated bearings and the plain bearings revealed a larger amount of stress induced microstructural alterations (white etching microstructure) at the maximum shear depth in the TDC plated bearings than in the plain bearings. This is further evidence that the TDC bearings were operating at a higher load, higher temperature, or both. **Figure** 46 shows the white etching regions in the TDC plated bearings and **Figure** 47 in the plain bearings.

Residual stress profiles of plain and TDC coated bearing inner rings after 2,500 hours of endurance testing, as shown in **Figures** 37 and 38 indicated both a large residual compressive stress in the area of the 0.010in deep for the TDC coated and a smaller and shallower (≈0.005in deep) subsurface compressive stress for the plain bearing. Since the depth of maximum shear stress is proportional to the contact area which in turn is proportional to the applied load and inversely proportional to the modulus of elasticity, it was concluded that the TDC bearing was either operating at a higher load, at a higher contact temperature, or both.

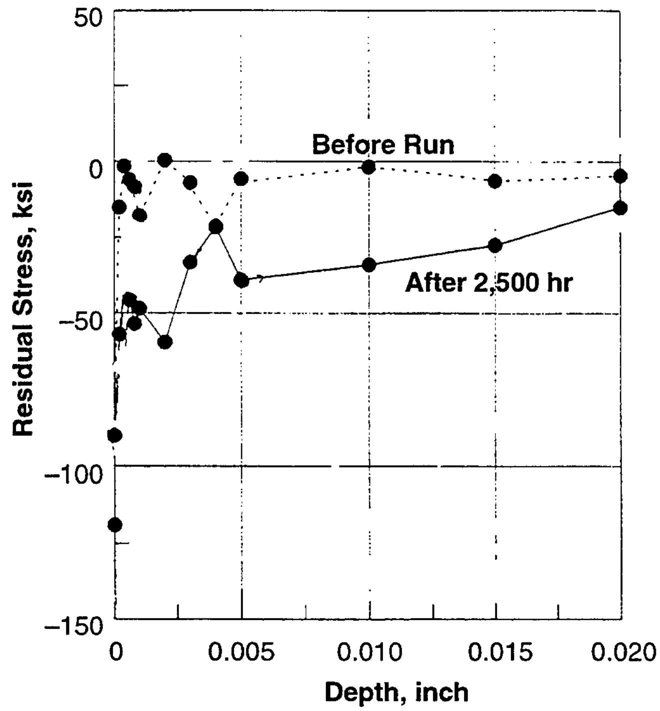


Figure 37. Residual Stress Profiles of MRC Round 1 Bare Baseline Rings. *Note the degree of change between the before and after the 2,500 hours is small when compared to the profile of the TDC coated bearings shown in Figure 38.*

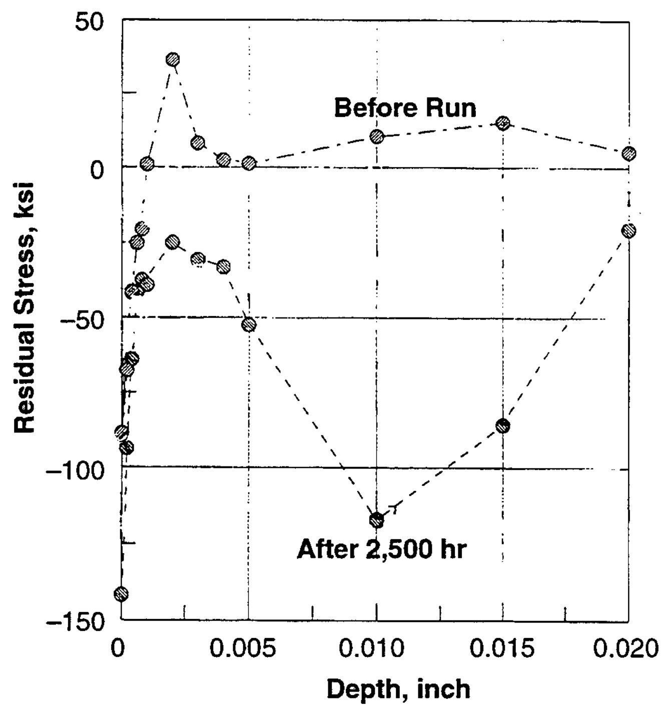


Figure 38. Residual Stress Profiles of MRC Round 1 TDC Coated Rings. *Note the Large compressive stress at 0.010 inch deep as a result of the 2,500 hours of operation.*

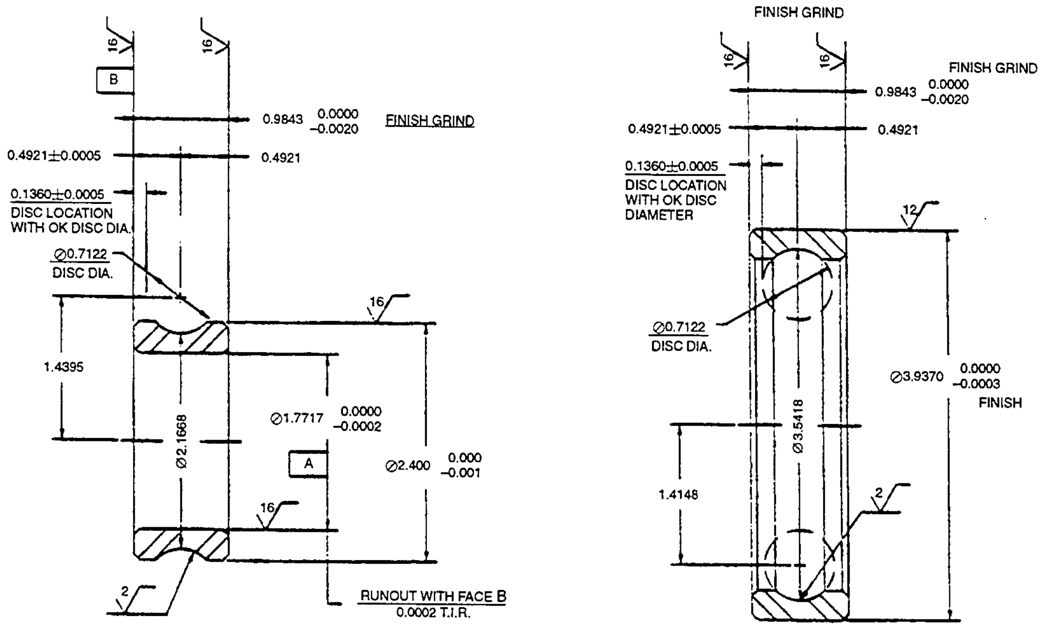


Figure 39. AEBC 5, 309–Size Ring Dimensions.

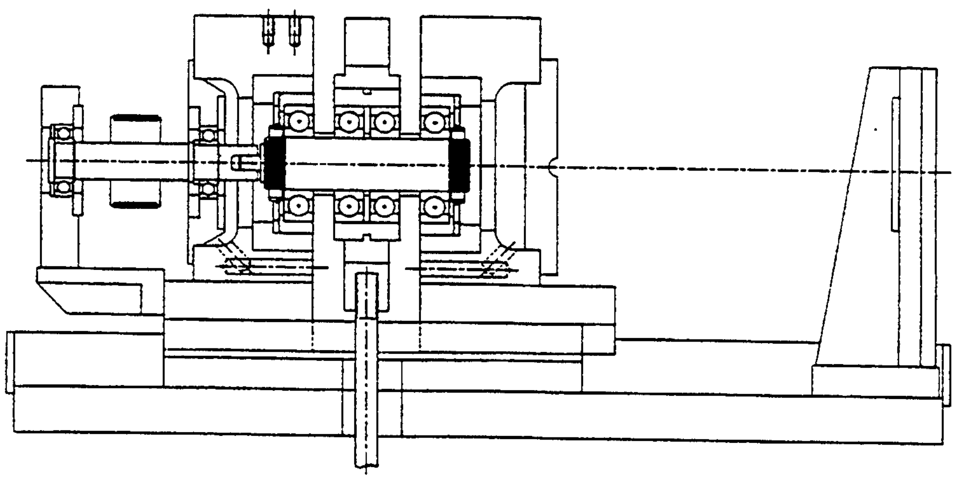


Figure 40. "G" Machine Configuration for Sudden Death Endurance Test.

Surface roughness measurements of the inner race ball track indicated its preplate roughness was approximately 1.7 μin, while its roughness postplating was on the order of 4 μin. This corresponds to an initial calculated Lambda around 1.7 to 2.0 for the plain bearings and around 0.9 for the TDC coated bearing. This likely explains why the ball tracks in the plain bearings are so difficult to see, and they are quite easily found in the TDC coated bearings. It is generally accepted that the fatigue life difference between a bearing with a Lambda of less than 1.0 to that of one in which it is greater than 1.5 can be very substantial, since the low lambda ratio bearing is much more prone to surface distress which can lead to early fatigue failure.

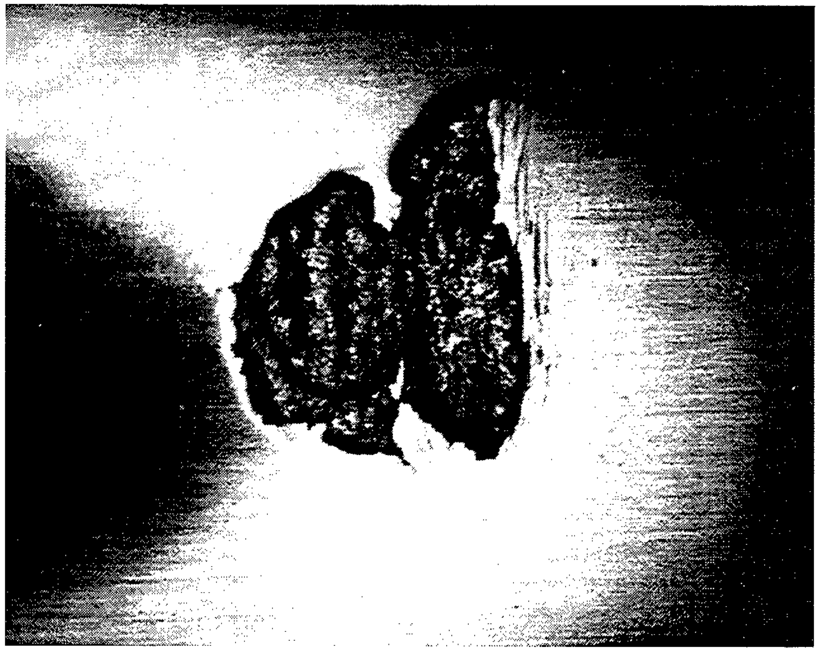
Table 9. Test Matrix of Baseline (no TDC) Test Bearings (MRC Round 1).

Bearing	Machine	Position	Total Hours	Comments
GE TDC 01	G1	1	2505.8	
GE TDC 02	G1	2	2505.8	
GE TDC 04	G2	1	2505.0	
GE TDC 08	G1	3	2505.8	
GE TDC 18	G1	4	2505.8	
GE TDC 22	G2	2	2505.0	
GE TDC 23	G2	3	2505.0	
GE TDC 28	G4	2	249.3	
GE TDC 29	G2	4	2505.0	
GE TDC 30	G4	1	249.3	
GE TDC 31	G5	1	2500.0	
GE TDC 32	G4	3	249.3	Inner Ring Spall
GE TDC 33	G5	2	2500.0	
GE TDC 34	G4	4	249.3	
GE TDC 36	G5	4	2500.0	
GE TDC 37	G5	3	2500.0	
GE TDC 40	G6	2	2508.9	
GE TDC 41	G6	1	2508.9	
GE TDC 42	G6	3	2508.9	
GE TDC 43	G6	4	2508.9	

Table 10. Test Matrix of TDC Test Bearings (MRC Round 1).

Bearing	Machine	Position	Total Hours	Comments
GE TDC 03	G6	1	1240.2	
GE TDC 05 *	G6	2	1240.2	Inner Ring Spall
GE TDC 06	G4	1	2609.6	
GE TDC 07	G4	2	2609.6	
GE TDC 09	G1	1	876.9	Inner Ring Spall
GE TDC 10	G2	1	802.9	
GE TDC 11	G2	2	802.9	
GE TDC 12	G2	3	802.9	
GE TDC 14	G4	3	2609.6	
GE TDC 15	G5	1	2152.1	
GE TDC 17	G4	4	2609.6	
GE TDC 19	G1	2	1181.0	Ball Spall
GE TDC 24	G5	2	2152.1	Inner Ring Spall
GE TDC 25	G6	3	1240.2	
GE TDC 26	G1	3	1181.0	
GE TDC 27 *	G1	4	1729.5	Inner Ring Spall
GE TDC 35	G5	3	2152.1	
GE TDC 38	G5	4	2152.1	
GE TDC 44	G6	4	1240.2	
GE TDC 45	G2	4	802.9	Inner Ring Spall

* As TDC 05 contained a grinding tear at the spall origin, and the numerous times TDC 27 had been assembled and disassembled caused concern about handling damage. These two bearings were not included in the Weibull analysis.

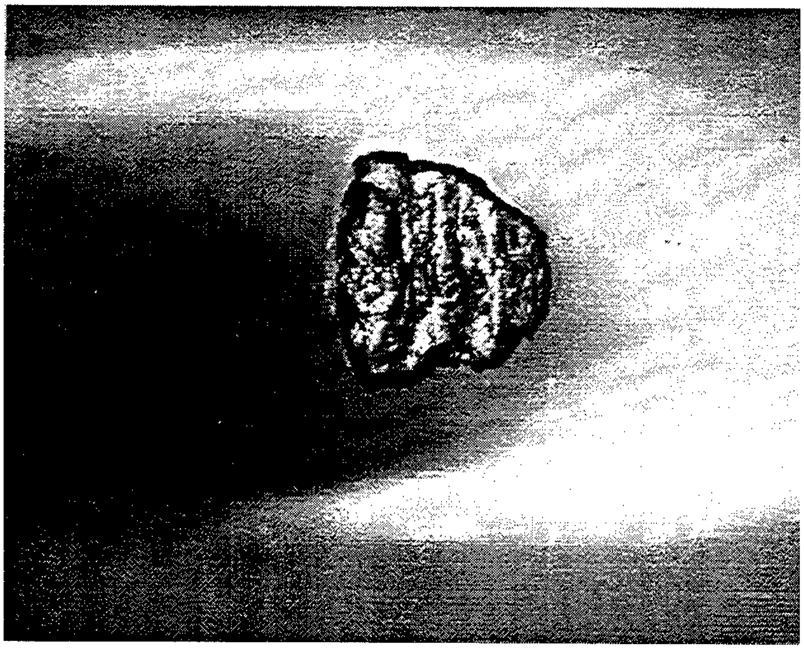


10X

Figure 41. SEM Photo of GE TDC 32 Inner Ring Spall from MRC Round 1.
Baseline plain bearing, 250 hours, only plain bearing failure.

30X

Figure 42. SEM Photo of GE TDC 24 Inner Ring Spall from MRC Round 1.
TDC plated bearing, 876 hours, one of three plated bearing failures.



10X

Figure 43. SEM Photo of GE TDC 09 Inner Ring Spall from MRC Round 1.
TDC plated bearing, 2152 hours, one of three plated bearing failures.

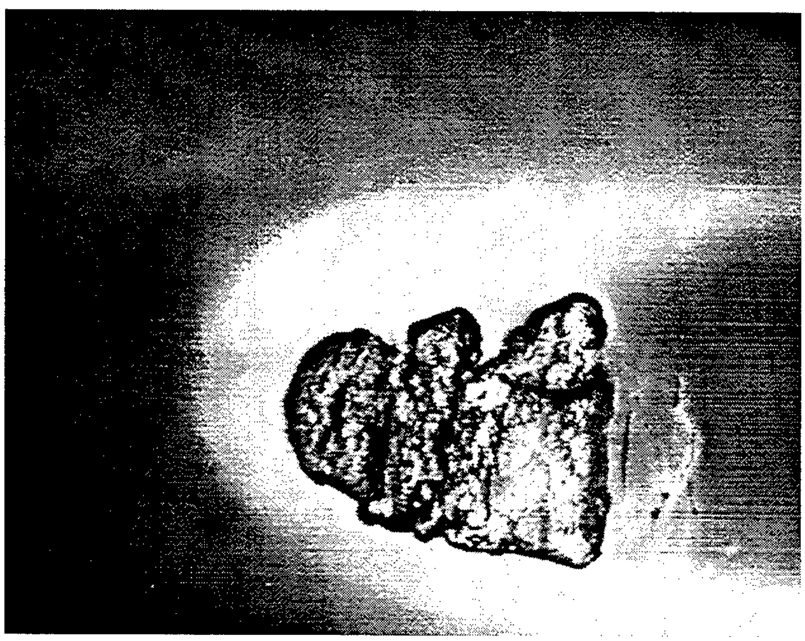


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Figure 44. SEM Photo of GE TDC 45 Inner Ring Spall from MRC Round 1.
TDC plated bearing, 802 hours, one of three plated bearing failures.

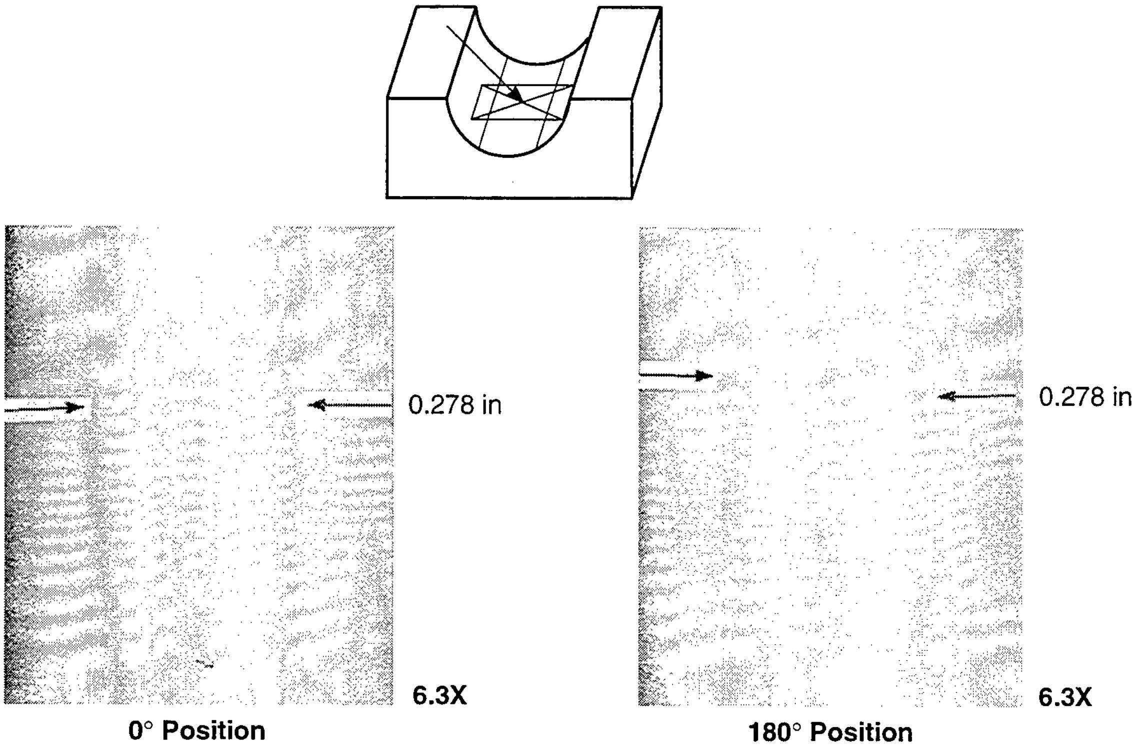
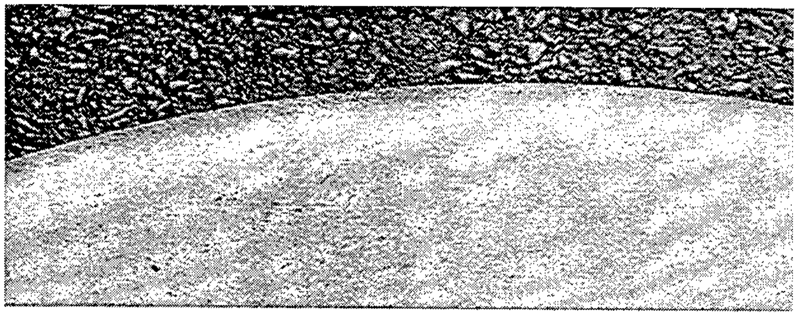


Figure 45. Photo of GE TDC 05 NTDC Plated Outer Race (MRC Round 1).
Wear track outer race locations at 0° and 180°.

A check of all the operating parameters indicated that the interference fits of the inner race to the supporting shaft led to some concern about the loss of operating clearance, particularly for the TDC coated bearings. It was thus determined that a second round of testing would be performed, in which the inner ring shafts would be match ground to the TDC bearing inner races, to give operating clearances similar to that of the baseline bearings.

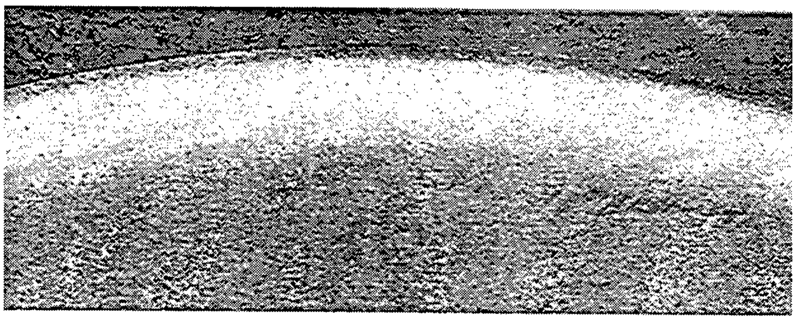
Of the two possible causes noted previously (Lambda and interference fit) for lower RCF life of the TDC plated bearings, the one which would be inherent to the process would be that of the TDC topography. With the TDC having a nodular topography, its starting surface roughness is greater than that of the plain bearings. This rougher surface could have the effect of lowering the Lambda during the early stages of bearing operation. A low Lambda could result in a bearing in which greater localized heat is generated, which in turn could cause a higher contact temperature, lowering the materials modulus and strength, driving the maximum shear stress deeper, and allowing it to cause microstructural alterations. Additionally, higher heat generation may cause the inner ring to heat up more than the outer ring forcing the loss of radial clearance, as was observed in the TDC coated bearings.

Although we were not able to ascertain if the interference fit or lambda played a role in the failures of the TDC plated bearings, it was decided that the best option was to repeat the test, making sure the set–up and operating conditions of the TDC bearings in the second round would mimic that of the plain bearings in Round 1. Ensuring operating clearance may reduce the amount of the stress induced microstructural alterations (white etching microstructure), but elimination of the stress is unlikely since the white layer was also observed in the plain bearings which reportedly operated with some radial clearance.



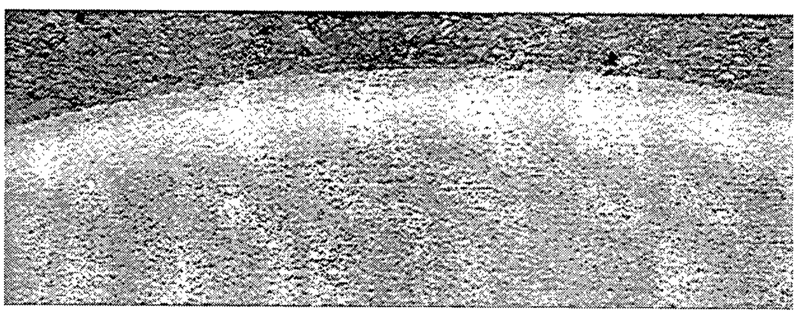
25X

Test No. 5, 1,240 Hours Operation



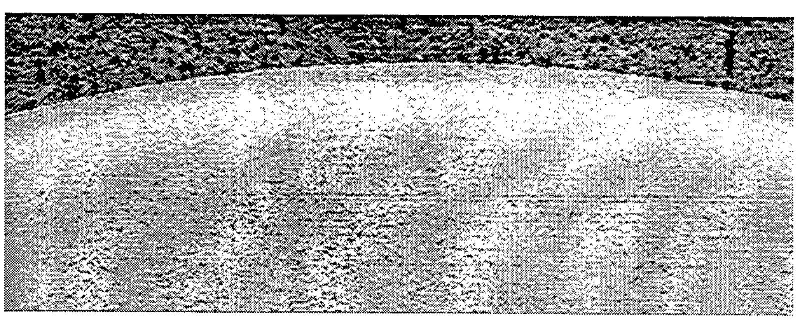
25X

Test No. 7, 2,500 Hours Operation



25X

Test No. 24, 2,152 Hours Operation



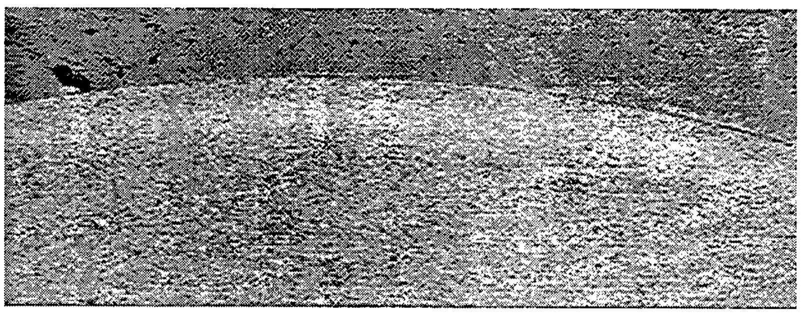
25X

Test No. 45, 802 Hours Operation

Figure 46. Optical Micrograph of MRC Round 1 TDC Test Balls.
Note white etching layer in max. shear zone.

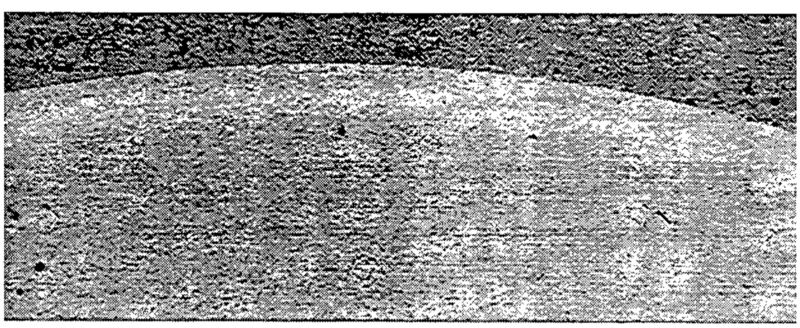
25X

Test No. 1, 2,500 Hours Operation



25X

Test No. 32, 249 Hours Operation



25X

Test No. 42, 2,500 Hours Operation

Figure 47. Optical Micrograph of MRC Round 1 Plain Test Balls. *Note lesser amount of white etching layer compared to balls from coated bearing balls, Figure 46.*

At this point we considered the endurance test screening as failed, and no vendor was certified.

4.2.2 MRC Round 2

4.2.2.1 Thickness Checks

PASSED

Table 11 shows the TDC thickness results of both the X–ray and Kocour method at three different locations of GE TDC 12 inner race from Round 2. **Table** 12 shows the thickness results for the inner rings plated for this second round of testing. The thicknesses generally fell within the range of 70 to 90 μin for the race and two faces, and from 95 to 105 μin on the two lands. The thicknesses are roughly 20 to 30μin thicker than were observed in Round 1. **Table** 13 shows the thickness results for the outer rings used in the second round of testing. The results are quite similar to those experienced in the first round.

4.2.2.2 Topography

FAILED

Scanning Electron Microscope inspection of an inner ring GE TDC 20 (**Figures** 48 through 51) indicated that the TDC coating lacked the typical well rounded nodules in the ball track and more importantly contained cracks in the TDC coating on the lands. The cracking is most evident at the 500X magnification and in the Backscatter Electron Imagery (BEI) mode on the SEM. This cracking in the lands led to concerns about how this lot would perform in the corrosion test. The lack of nodularity in the ball track may in fact have contributed to the improved RCF results noted later in this report.

4.2.2.3 Corrosion Testing

FAILED

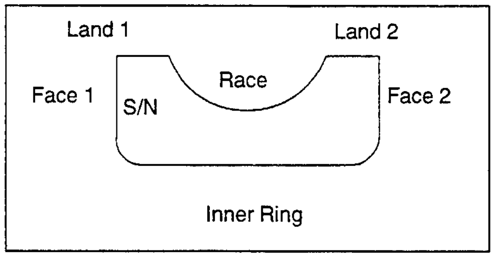
Prior to testing, inner ring GE TDC 31 was evaluated on the SEM to determine if it contained cracks as was seen in S/N 20. **Figures** 52 through 61 show the topography of this bearing. Cracks were evident at the edge of the raceway track and the edge of the land. Upon completion of the 24–hour salt spray testing, numerous rust spots appeared on this specimen (**Figure** 62) and it was deemed to have failed this test. This result was also confirmed with inner race GE TDC 18. It contained a similar amount of corrosion after a salt spray test. The amount of corrosion in Round 2 was considerably greater than that exhibited in Round 1. Test results are in Appendix B.

Table 11. GE TDC 12 Inner Race Thickness Measurements (MRC Round 2), μin.
All data is within spec.

Position	X-ray Method			Kocour	
	Land #1	Raceway	Land #2 (GE TDC)	Bore	
0°	89.3	62.1	93.2	80	80
120°	89.3	79.0	92.1	85	85
240°	87.2	64.4	92.6	85	90

Additional Raceway (X-ray Method)				
position	0°	90°	180°	270°
measurement	61.5	66.9	80.7	60.8

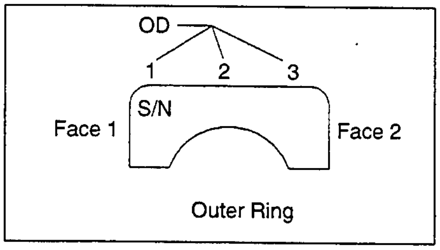
Table 12. Armoloy Inner Ring Thickness Measurements (MRC Round 2), μin.
All data is within spec.



S/N	Race	Face 1	Face 2	Land 1	Land 2
1	90.4	86.8	86.4	108.5	128.1
2	85.3	83.5	82.2	105.3	106.8
3	84.8	80.7	74.4	97.3	103.6
4	85.8	76.7	79.5	101.0	101.7
5	70.3	75.2	72.6	92.4	90.2
6	74.1	81.1	79.4	98.6	98.3
7	92.7	86.6	84.8	108.5	114.9
8	74.0	70.3	79.1	93.3	94.9
9	71.4	76.9	80.8	99.2	97.9
10	87.2	77.2	78.7	101.6	104.6
11	88.0	77.2	77.5	99.4	105.1
12	68.5	75.8	72.0	95.1	91.6
13	78.5	73.1	83.5	105.6	106.7
14	81.3	82.4	79.6	104.0	107.5
15	80.0	75.9	79.4	97.0	104.5
16	74.1	79.3	86.1	98.6	102.7
17	79.7	78.6	81.2	96.8	105.8
18	80.3	78.9	77.8	97.2	95.7
19	80.9	76.1	75.8	98.0	100.0
20	75.1	79.5	80.6	100.2	106.9
21	80.7	77.9	76.0	100.9	100.4
22	81.5	77.2	81.4	98.7	100.6
23	81.5	76.8	74.8	100.9	96.0
24	84.1	80.6	76.7	104.8	96.5
25	89.5	83.8	83.6	109.5	111.4
26	81.7	79.1	78.3	99.5	101.3
27	73.7	80.0	78.3	97.0	100.8
28	83.8	79.1	77.8	108.6	102.0
29	80.8	79.6	79.8	103.5	102.5
30	76.3	77.9	79.4	100.1	99.9
31	82.1	81.6	79.4	101.2	102.3

Note: Shaded boxes indicate "No Bake" rings

Table 13. Armoloy Outer Ring Thickness Measurements (MRC Round 2), µin. *All data is within spec.*

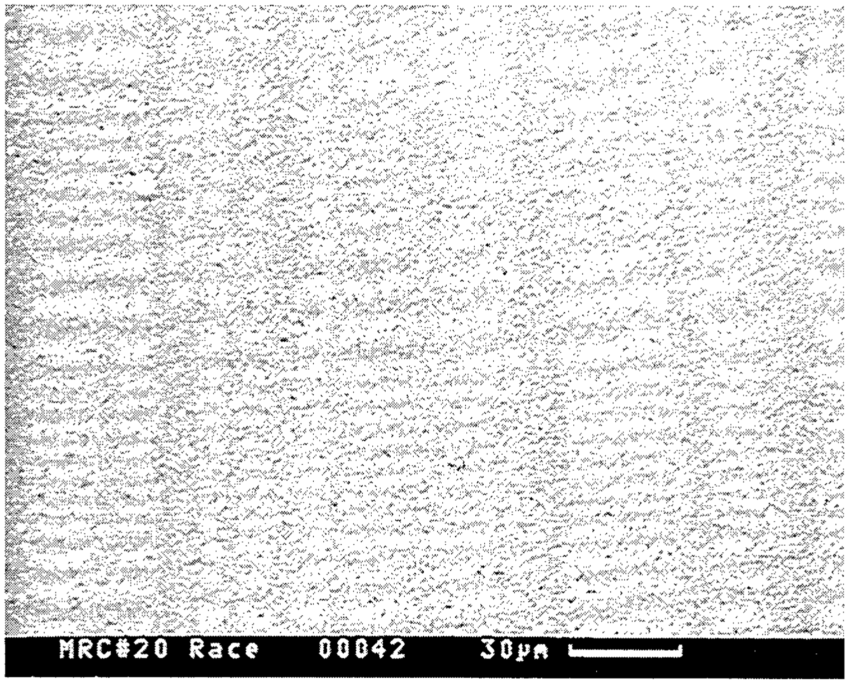


S/N	Face 1	Face 2	OD 1	OD 2	OD 3
1	57.7	59.0	64.7	57.3	67.5
2	76.2	77.5	88.9	83.0	91.0
3	60.8	62.8	73.2	76.3	81.8
4	*	*	*	*	*
5	81.3	73.9	94.6	91.1	90.6
6	64.9	64.8	79.0	72.9	76.6
7	*	*	*	*	*
8	52.8	45.2	58.6	52.3	59.4
9	43.8	55.7	60.3	51.2	56.6
10	49.0	62.5	67.6	58.6	71.8
11	60.7	65.1	39.8	70.4	85.2
12	60.6	52.6	58.4	43.2	53.4
13	46.1	53.9	65.7	55.4	63.3
14	65.2	58.2	77.9	70.2	73.8
15	54.2	52.5	85.9	80.5	81.4
16	*	*	*	*	*
17	53.5	57.7	67.3	57.7	66.6
18	63.9	66.1	85.4	78.1	79.0

S/N	Face 1	Face 2	OD 1	OD 2	OD 3
19	56.3	58.6	77.8	72.6	75.5
20	62.0	53.3	75.7	67.7	72.2
21	64.1	67.4	80.1	73.4	76.1
22	50.6	57.6	59.8	53.0	61.4
23	70.3	71.3	87.3	76.2	90.3
24	76.4	59.3	76.3	74.2	78.5
25	60.4	64.7	80.6	78.2	81.3
26	57.1	56.1	71.2	68.4	70.7
27	65.6	62.9	73.0	65.5	74.9
28	60.9	64.7	76.9	75.5	85.5
29	62.4	56.7	74.4	65.2	77.0
30	54.7	54.7	69.1	60.0	67.4
31	64.1	64.7	78.6	68.9	78.6

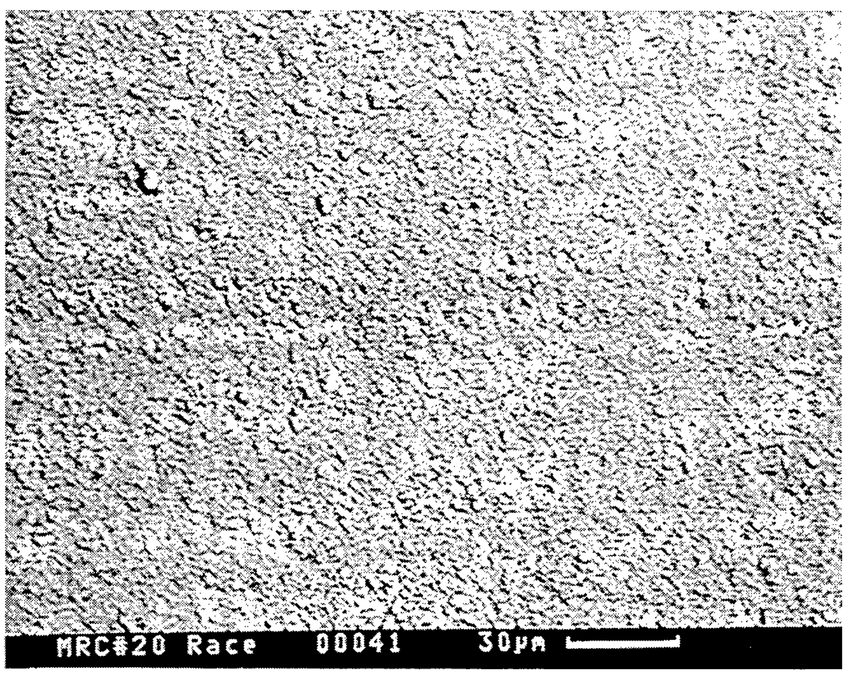
* An error has ocurred with the thickness measurements. Two readings were recorded for S/N 7, there are no recordings for S/N's 4 and 16.
Shaded boxes indicate "No bake" rings

Note: Shaded boxes indicate "No Bake" rings



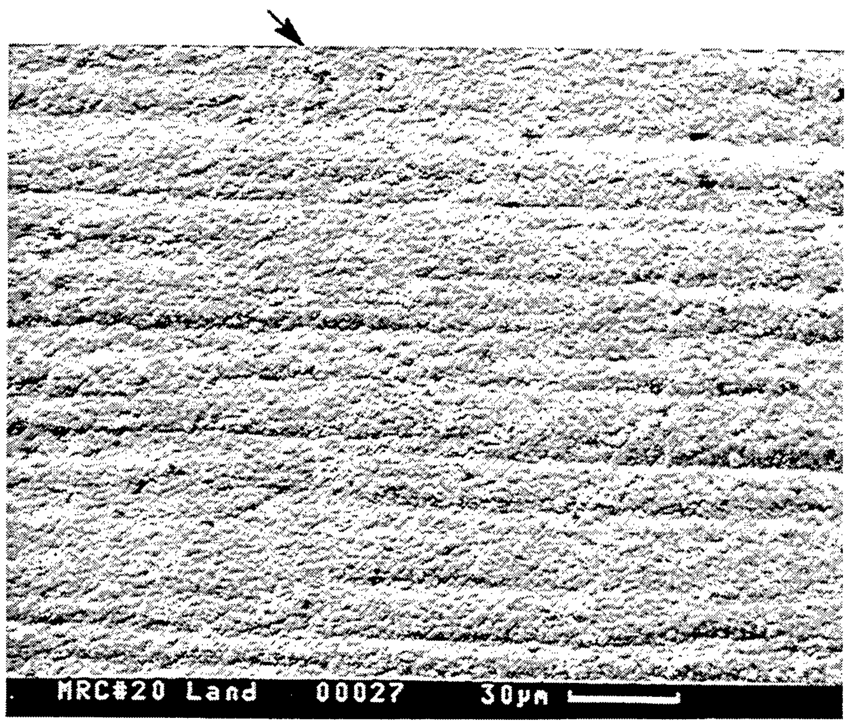
500X

Figure 48. SEM Photo of Bearing Raceway, SEI Mode. *Note lack of nodularity, coating appears somewhat flat.*



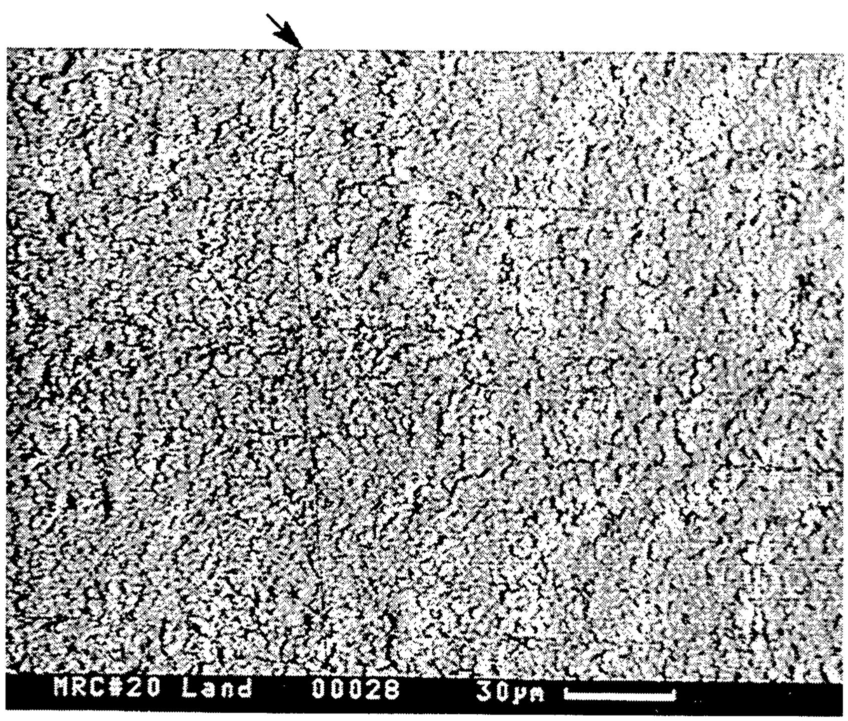
500X

Figure 49. SEM Photo of Bearing Raceway, BEI Mode. *Note lack of typical TDC nodularity.*



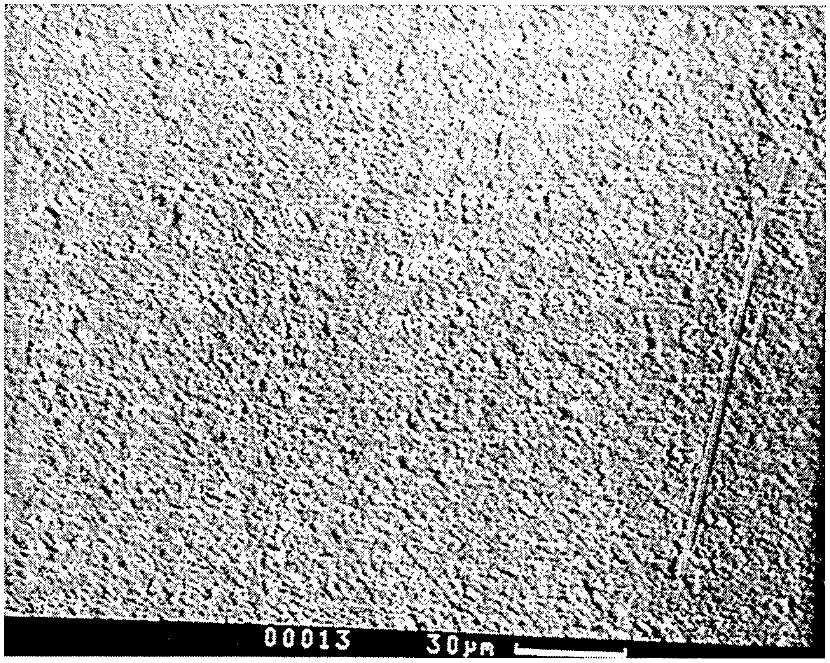
500X

Figure 50. SEM Photo of Bearing Land, SEI Mode.
Note crack in TDC coating.



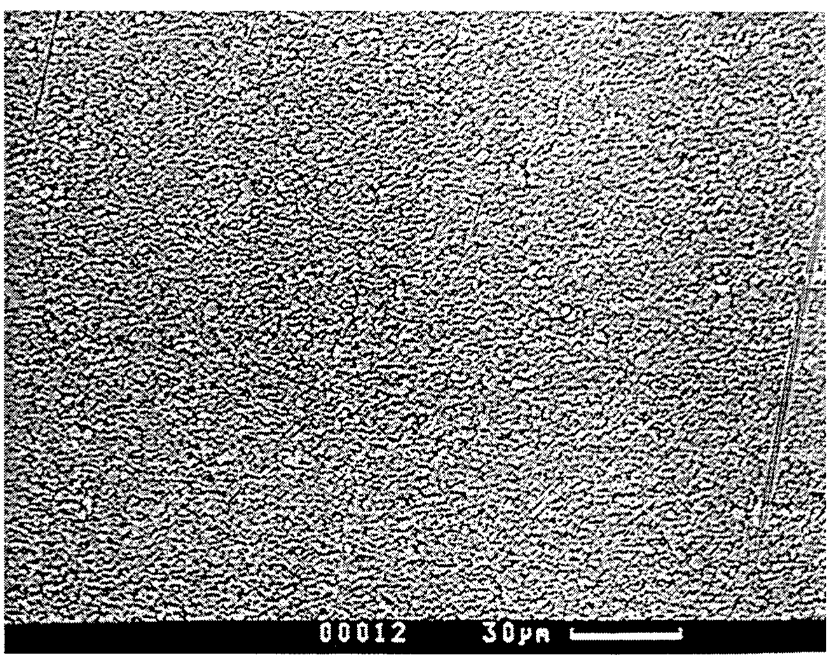
500X

Figure 51. SEM Photo of Bearing Land, BEI Mode.
Note crack in TDC coating.



500X

Figure 52. SEM Photo of Center of Bearing Raceway, SEI Mode.
Note lack of nodularity.



500X

Figure 53. SEM Photo of Center of Bearing Raceway, BEI Mode.
Coating is intact in this area.

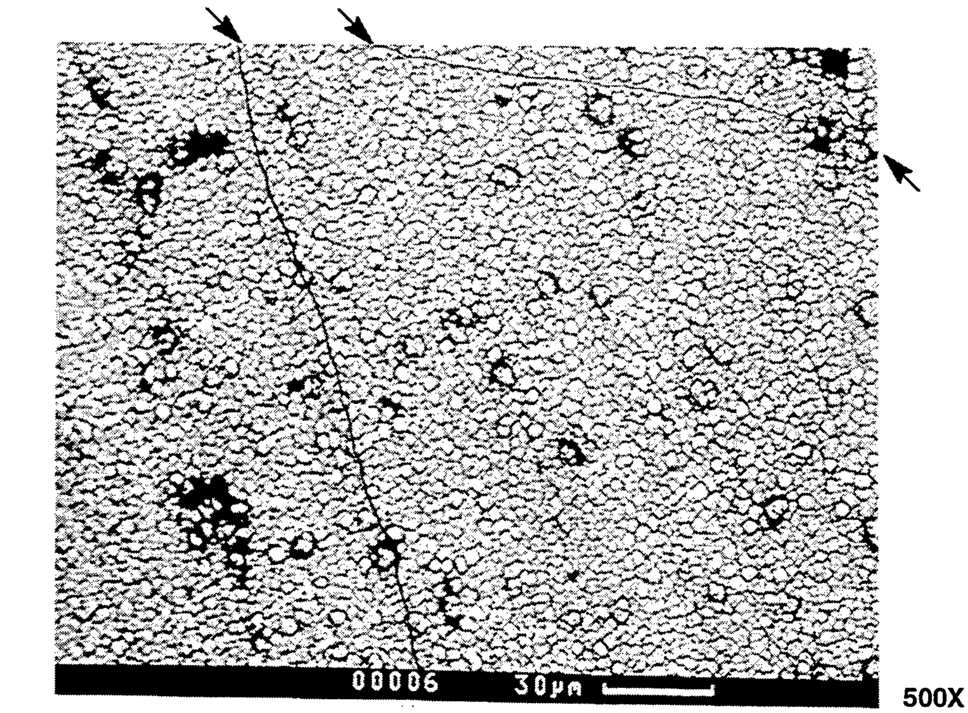


Figure 54. SEM Photo of Edge of Bearing Raceway Track, BEI Mode.
Note cracks.

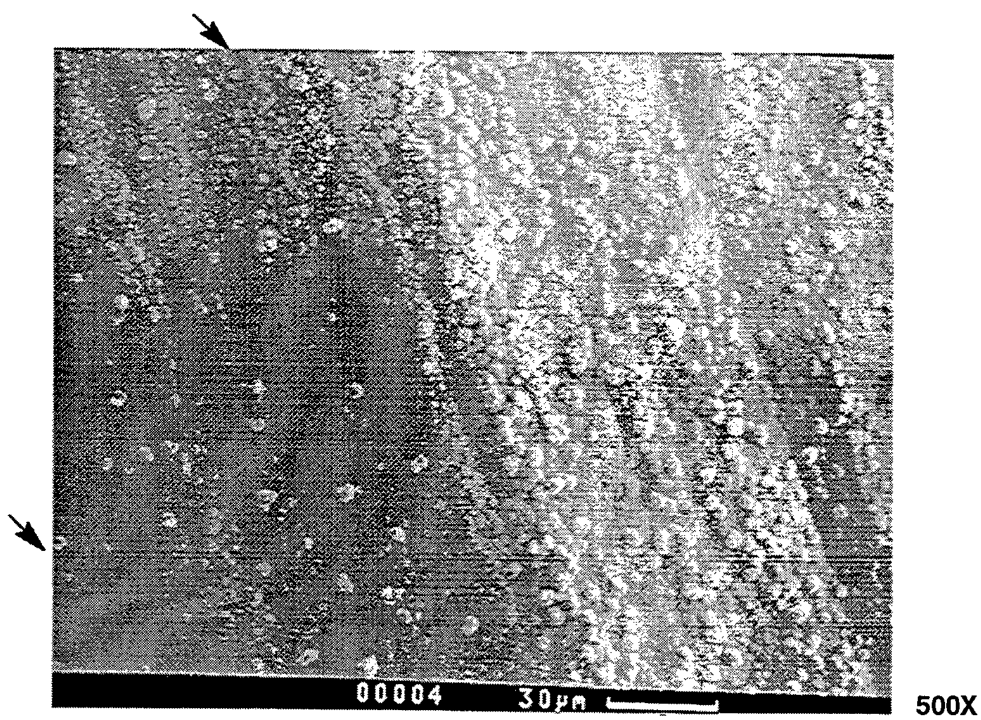
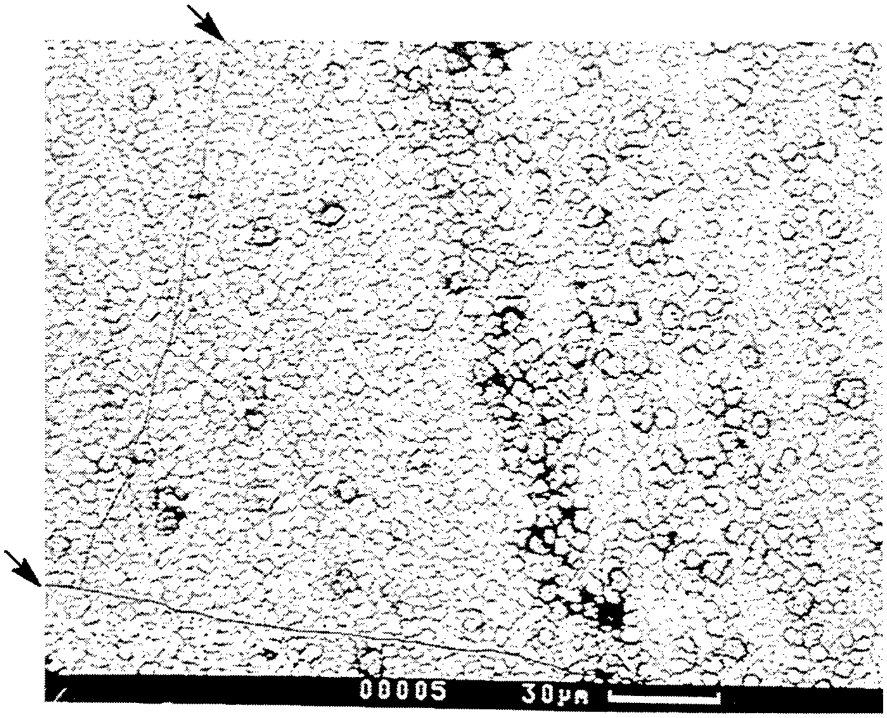
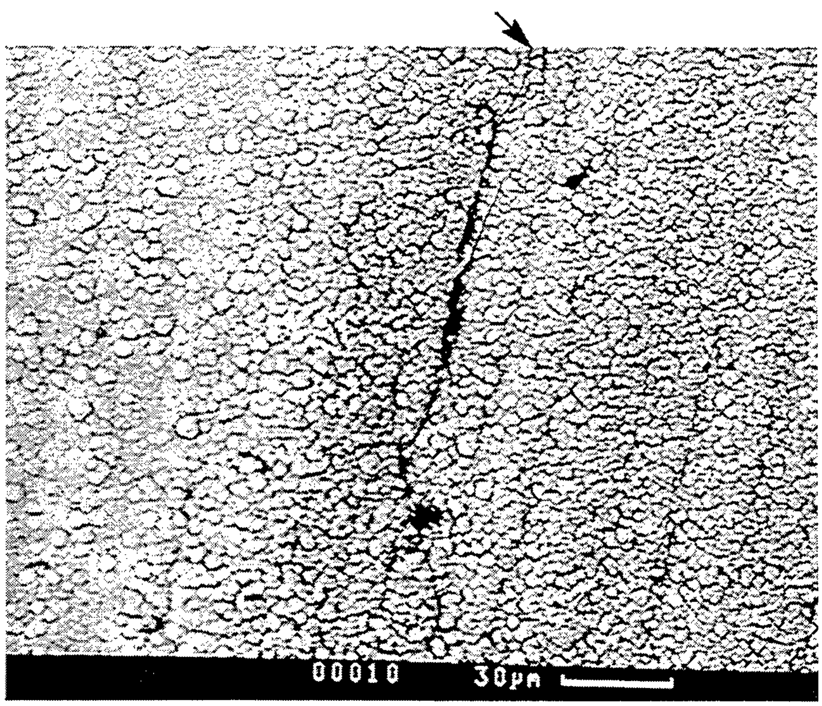


Figure 55. SEM Photo of Edge of Land No. 1, SEI Mode.
Note chrome clusters and cracks.



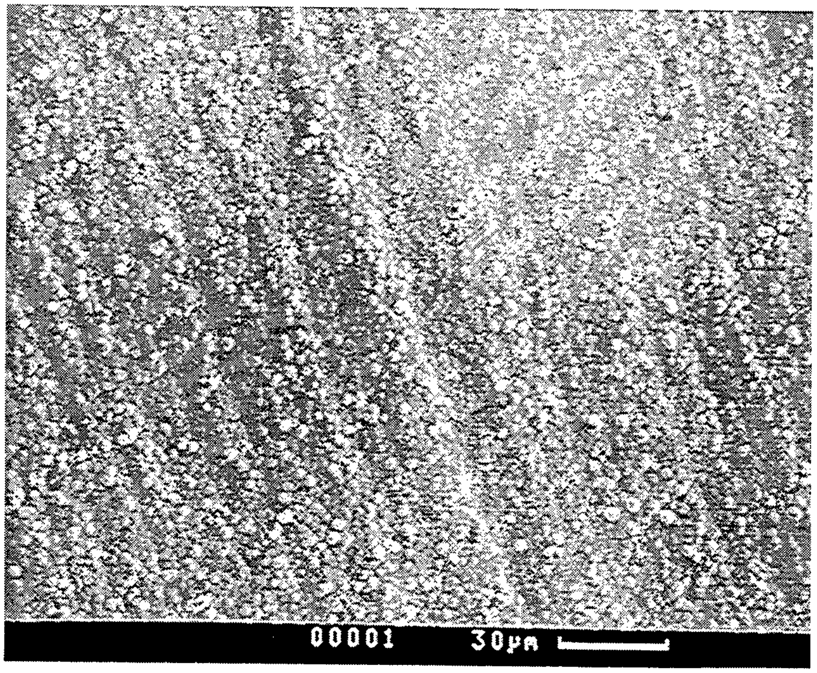
500X

Figure 56. SEM Photo of Edge of Land No. 1, BEI Mode.
Note crack in same area as Figure 55 highlighted in BEI mode.



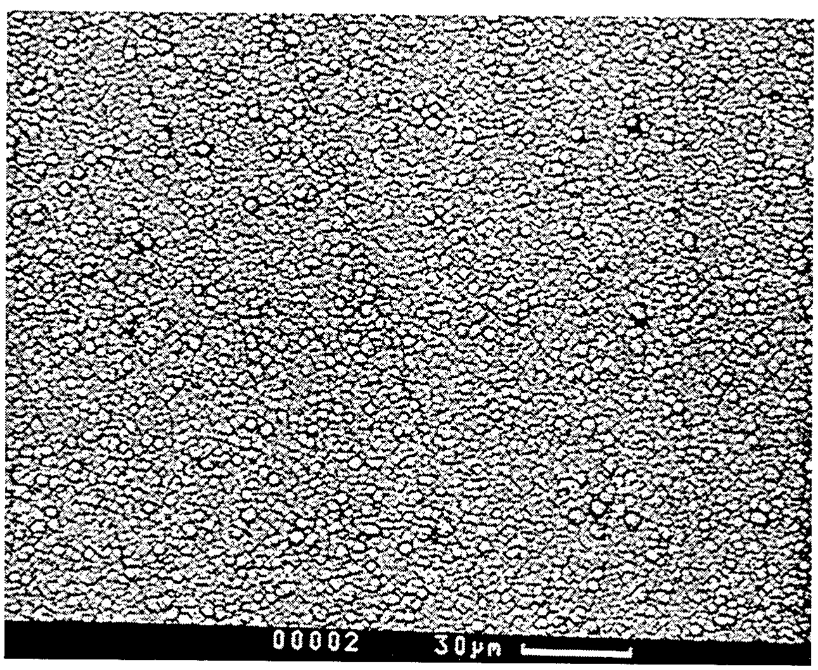
500X

Figure 57. SEM Photo of Edge of Land No. 2, BEI Mode.
Note crack.



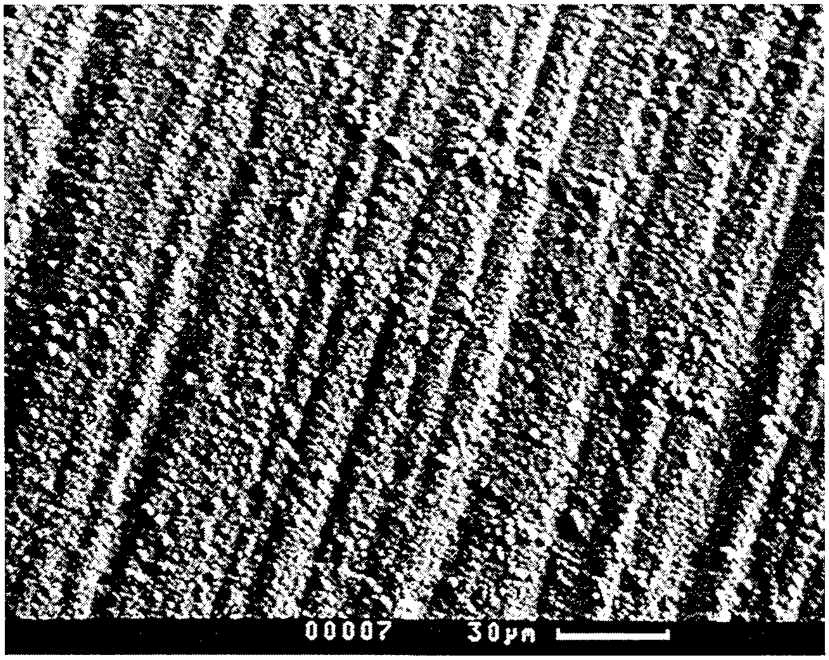
500X

Figure 58. SEM Photo of Center of Land No. 1, SEI Mode.



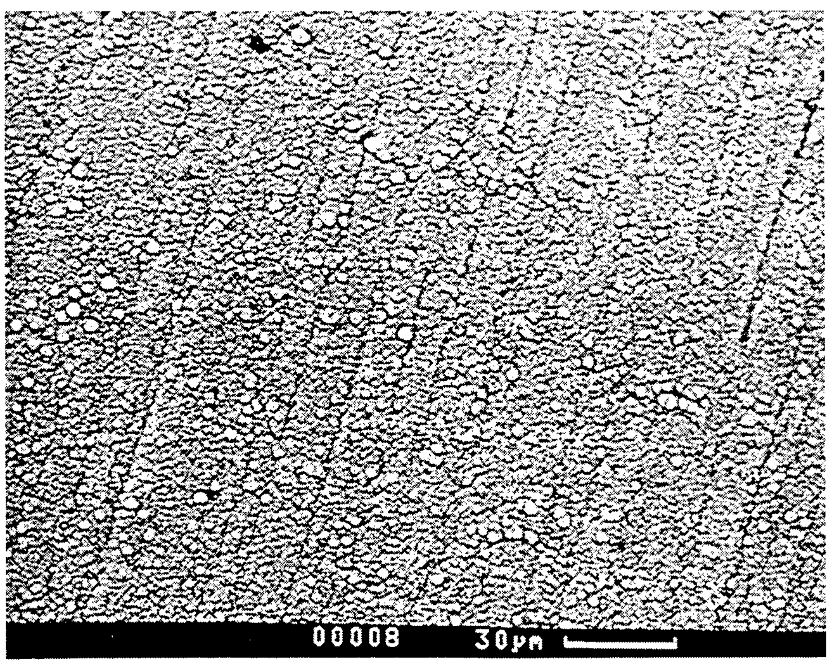
500X

Figure 59. SEM Photo of Center of Land No. 1, BEI Mode.



500X

Figure 60. SEM Photo of Center of Land No. 2, SEI Mode.



500X

Figure 61. SEM Photo of Center of Land No. 2, BEI Mode.

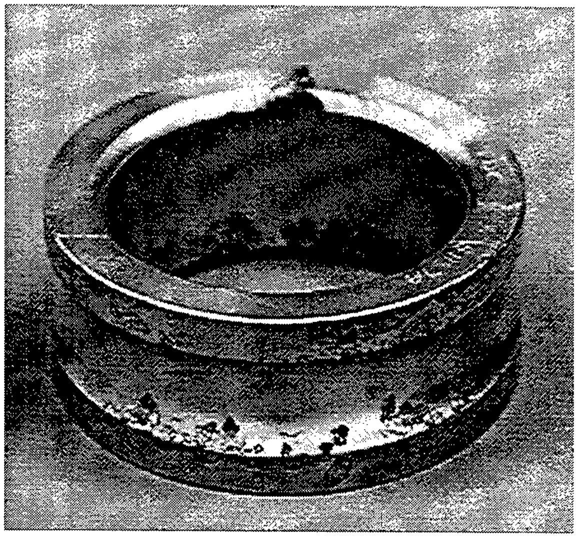


Figure 62. Photo of GE TDC 31 Inner Ring Corrosion after Salt Spray Test. *Note large amount of rust.*

4.2.2.4 Hydrogen Embrittlement

FAILED

Three notched tensile samples were suspended at 75% of the average ultimate tensile load of M50. Two of the specimens were suspended for 200 hours, however the third specimen failed within 2.5 hours of loading. Posttest hydrogen determination indicated that the failed specimen and the surviving specimens all contained about the same amount of hydrogen, approximately 2.5 ppm. This type of a result would be consistent with a sample which had completed the required postplate baking process, but possibly the time between plating and baking was greater than the 1 hour maximum allowed in the GE specification. This delay could account for the premature failure, although the vendor certified the parts were made to the specification. Certification of the test results appear in Appendix B.

4.2.2.5 Wear Testing

PASSED

Taber wear data indicated a wear index of 0.8 (an average of 4.4 milligrams weight loss) for the three specimens tested. This was less than the requirement of a wear index ≤1.2. Weight losses for the three specimens were 4.4, 4.5, and 4.3 mg/5000 cycles.

4.2.2.6 Adhesion Testing

PASSED

Postbend test inspection indicated that the TDC coating adhered to the base metal, and did not flake, peel, chip, or delaminate.

4.2.2.7 Thermal Shock Testing

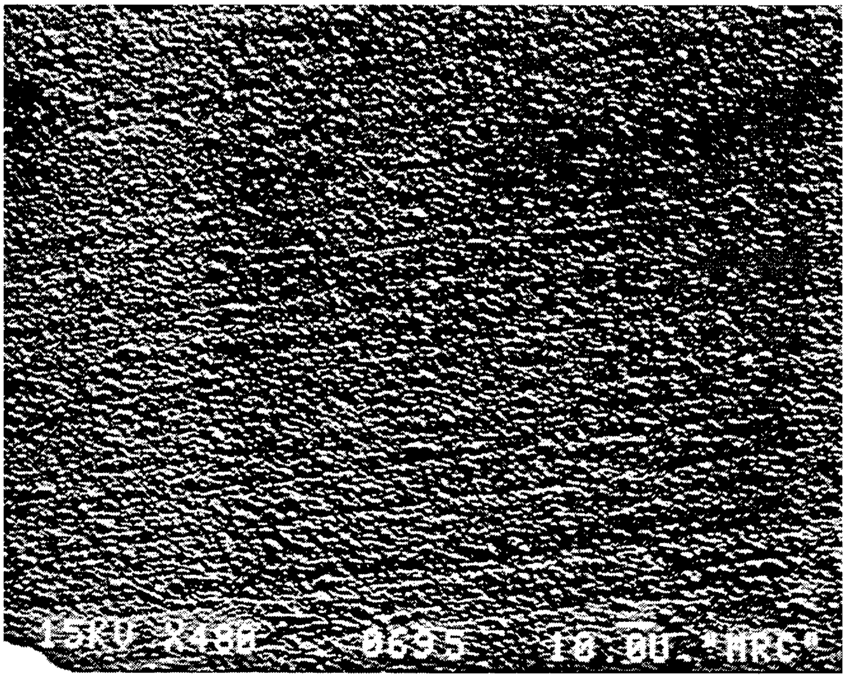
PASSED

Two outer rings were subjected to the 10 thermal shock cycles. SEM examination revealed cracking in the race to the edge of the land. Initially this was considered a failing mark, but after taking into consideration the other cracks which were observed on as–received rings, it was felt that this cracking was not caused by the thermal cycling, but was already present in the specimen prior to thermal cycling. This was supported by the presence of cracking on just one of the land/race edges and not both. If this was thermal cycle induced, both sides would have cracked. **Figures** 63 through 70 show the raceway and the land/raceway edge at four locations around the bearing. The TDC in the edge area that was cracked (90° position) is a mix of flat and chrome clusters, and would not have passed the GE Photo Standard. This condition was not caused by thermal cycling, but was an as–plated condition.

4.2.2.8 Residual Stress

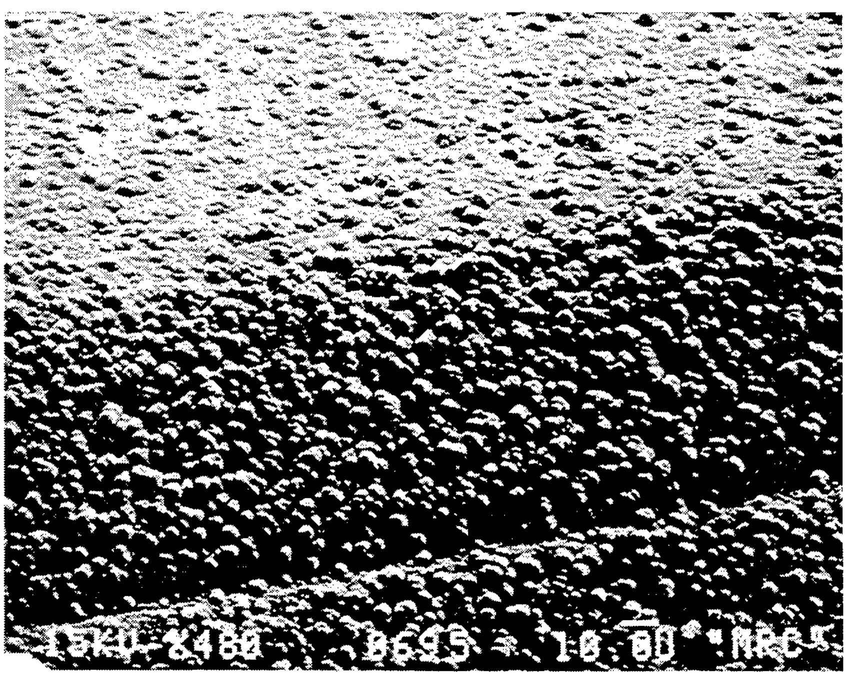
PASSED

X–ray diffraction testing of Outer Ring 31 indicated that the TDC was in a state of residual compressive stress, as required.



500X

Figure 63. SEM Photo of Raceway, 0°. *Note lack of nodularity.*

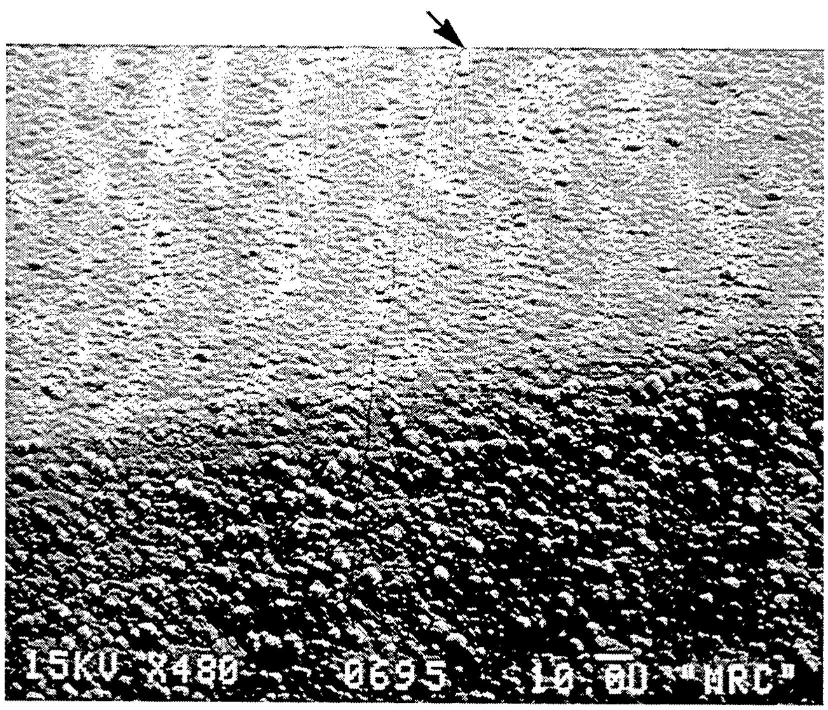


500X

Figure 64. SEM Photo of Race/Land Edge, 0°. *Note mix of nodularity, both flat and nodular areas exist in the race/land edge.*

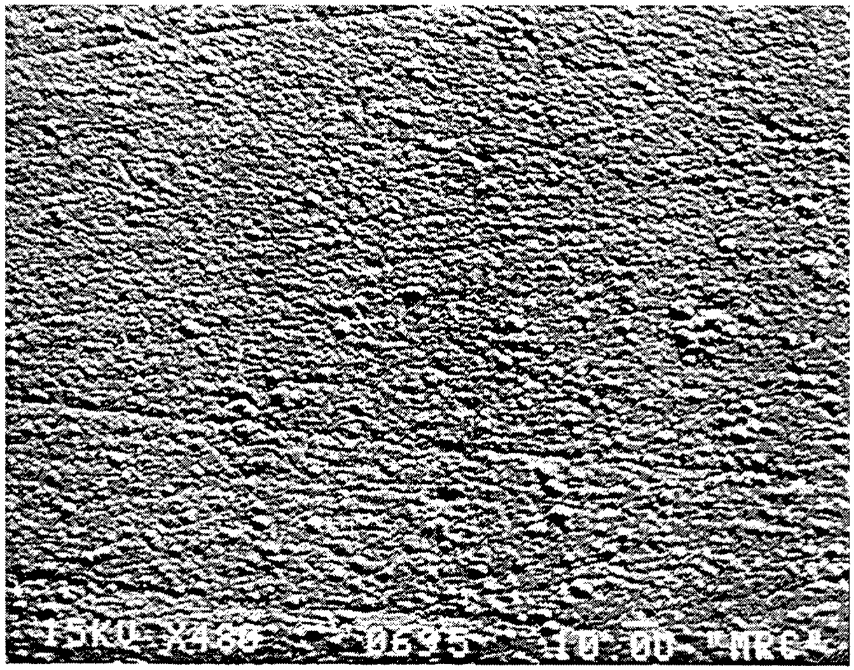
500X

Figure 65. **SEM Photo of Raceway, 90°.** *Note lack of nodularity.*



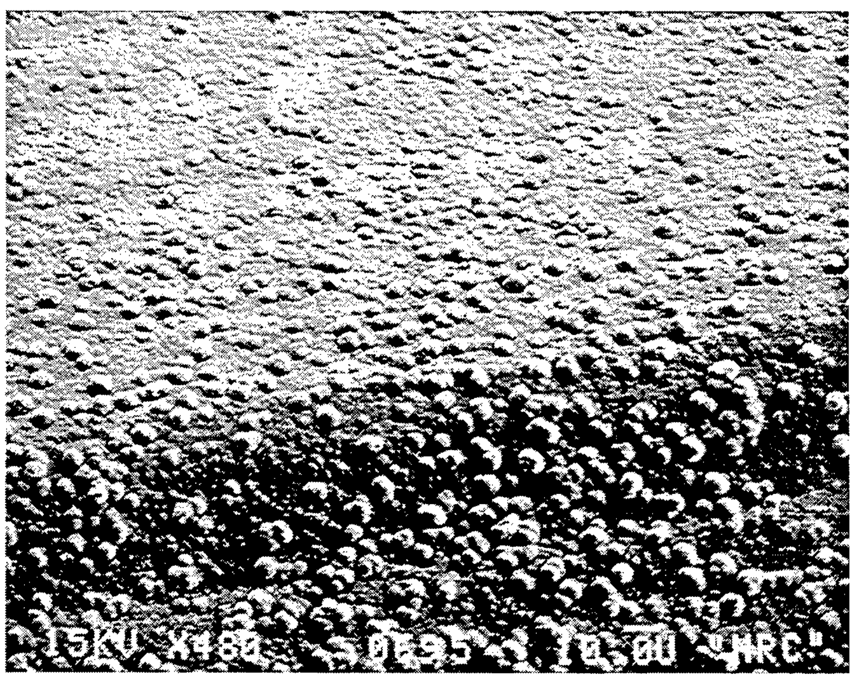
500X

Figure 66. **SEM Photo of Raceway, 90°.** *Note crack.*



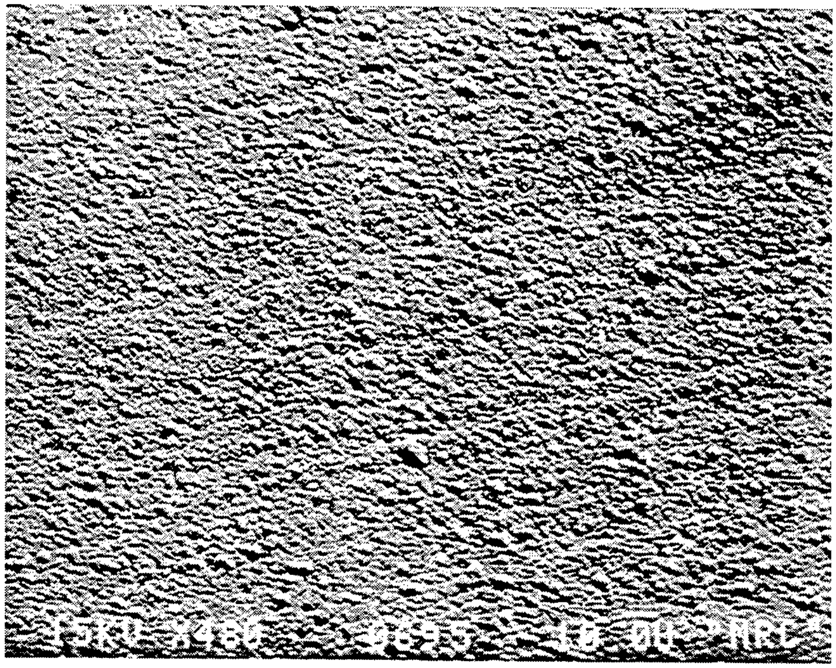
500X

Figure 67. SEM Photo of Raceway, 180°. *Note lack of nodularity.*



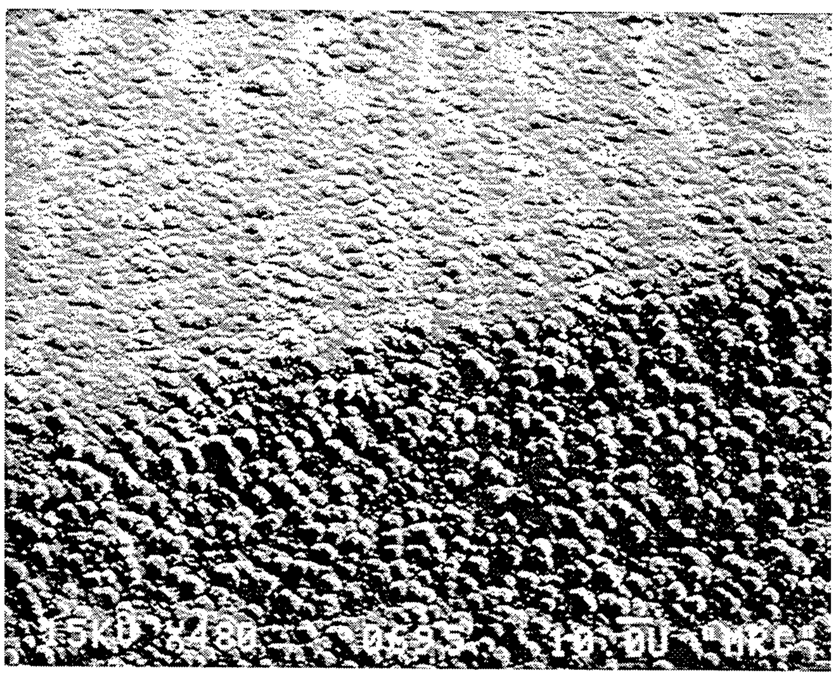
500X

Figure 68. SEM Photo of Raceway, 180°. *Note chrome nodules on top of a relatively flat surface.*



500X

Figure 69. SEM Photo of Raceway, 270°. *Note lack of nodularity.*



500X

Figure 70. SEM Photo of Race/Land Edge, 270°. *Note chrome nodules on top of a relatively flat surface.*

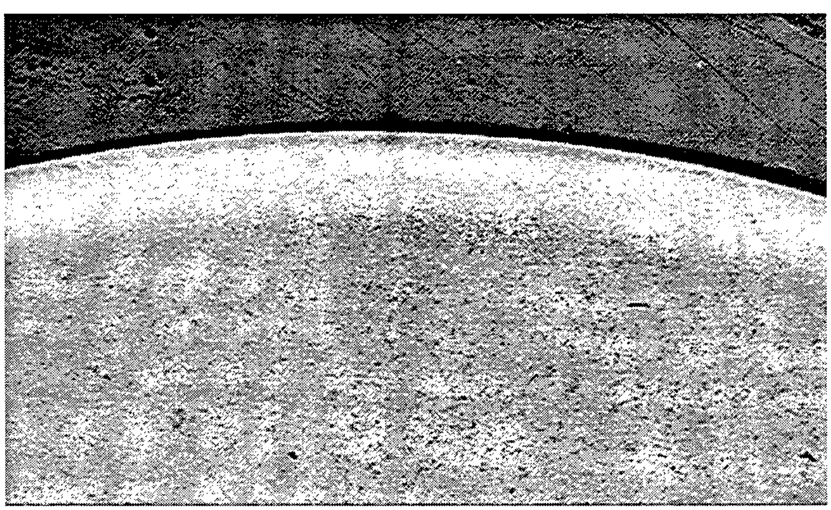
4.2.2.9 Rolling Contact Fatigue

PASSED

RCF testing involved running TDC plated bearings and comparing the results back to that of the baseline (unplated) bearings run in Round 1. In addition to the 20 plated and baked bearings, 4 plated and not baked bearings (S/N's 8, 9, 12, and 22) were run. None of the 24 bearings failed in this series of tests, all were run 2,500 hours at 475 ksi. Although the L10 was not calculated, it was concluded that in this round the TDC–plated bearings performed at least equal to the unplated bearings from Round 1. Two differences were noted from the first round of TDC testing. First was the care given to match grinding the shafts to obtain similar operating internal running clearances, and the second was the surface topography of the TDC in the ball track. The TDC was relatively flat in this round of tests. Measurements taken on the inner race of GE TDC 20 from Round 1 indicated an as–plated surface roughness of 7.4 μ inch Ra in the raceway. The inner race of GE TDC 27 from Round 2 had an as–plated roughness of 5.0 μ inch Ra in the raceway. This difference could affect the Lambda value, particularly early in the testing cycle before the nodules are flattened or smoothed out

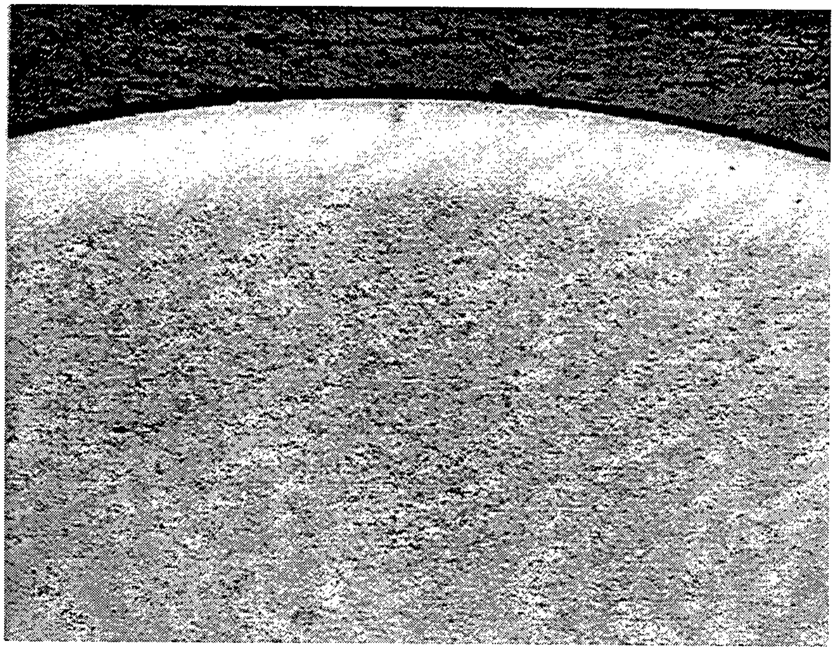
A comparison of balls from four suspended (2,500 hour) bearings to the balls from the Round 1 plain and TDC–coated bearings (**Figures** 46 and 47) indicated that the Round 2 stress induced microstructural alterations were between the two Round 1 bearings, looking more similar to balls run in the TDC coated races. However, none of the balls from the second round, **Figures** 71 through 74, exhibited as much of a white layer as did the Round 1 TDC 7 ball. This would indicate that although opening up the bearing clearance in Round 2 helped the rolling contact fatigue results, there is still some unique aspect of the TDC coating which appeared to increase either the stress or operating temperature of the bearings above that of the plain bearings.

A macroscopic inspection of the outer races indicated that the ball tracks were much harder to see than the TDC bearings of Round 1, an indication that the Lambda was better. Additionally, the ball track of the new Round 2 bearings was not as matte in appearance and was somewhat reflective, indicating that the TDC was smoother and not as nodular as in Round 1. A macroscopic inspection of the inner races indicated that the TDC was also less matte in appearance than the inner races in Round 1.



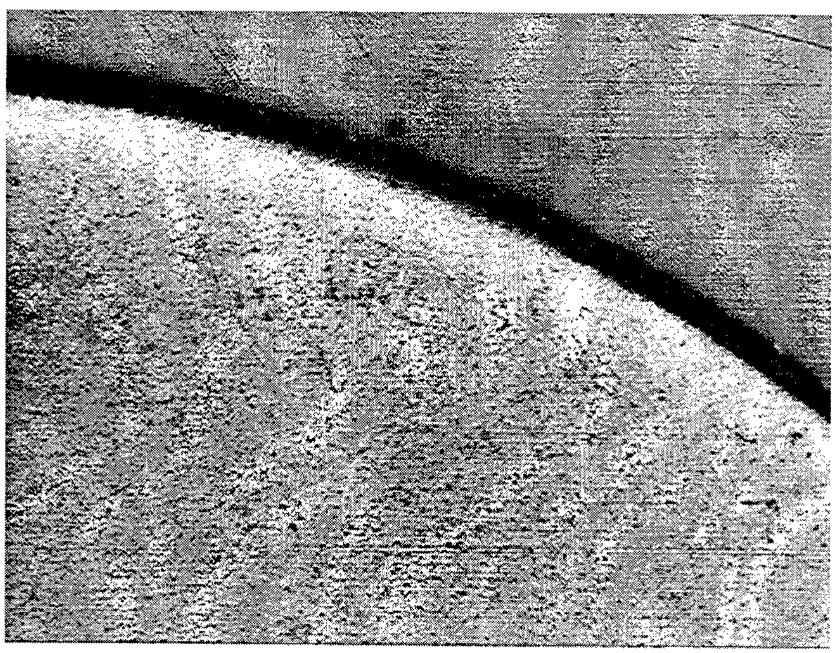
25X

Figure 71. Subsurface Stress Induced Microstructural Alteration (White Layer) in Ball from Round 2/Test 1. *The layer covered the entire ball indicating the ball was spinning.*



25X

Figure 72. Subsurface Stress Induced Microstructural Alteration (White Layer) in Ball from Round 2/Test 4. *The layer covered the entire ball indicating the ball was spinning.*



25X

Figure 73. Subsurface Stress Induced Microstructural Alteration (White Layer) in Ball from Round 2/Test 6. *The layer was in a circumferential line indicating the ball was tracking.*

Figure 74. Subsurface Stress Induced Microstructural Alteration (White Layer) in Ball from Round 2/Test 11. *The layer covered the entire ball indicating the ball was spinning.*

4.2.3 SBB Round No. 1

4.2.3.1 Thickness Checks

PASSED

Optical metallurgical microscope photographs at 1000X indicated the following TDC thickness for the inner and outer races of the 5HTH 207 bearing.

Surface	Thickness (μin)
Inner Ring	
Raceway	65
OD/land	80
Face	105
Bore	100
Outer Ring	
Raceway	85
Land	140
Face	60
OD	100

Figures 75 through 85 show the optical photomicrographs used to determine the TDC thickness in the locations noted above. The thickness values all fell within the GE Specification.

4.2.3.2 Topography

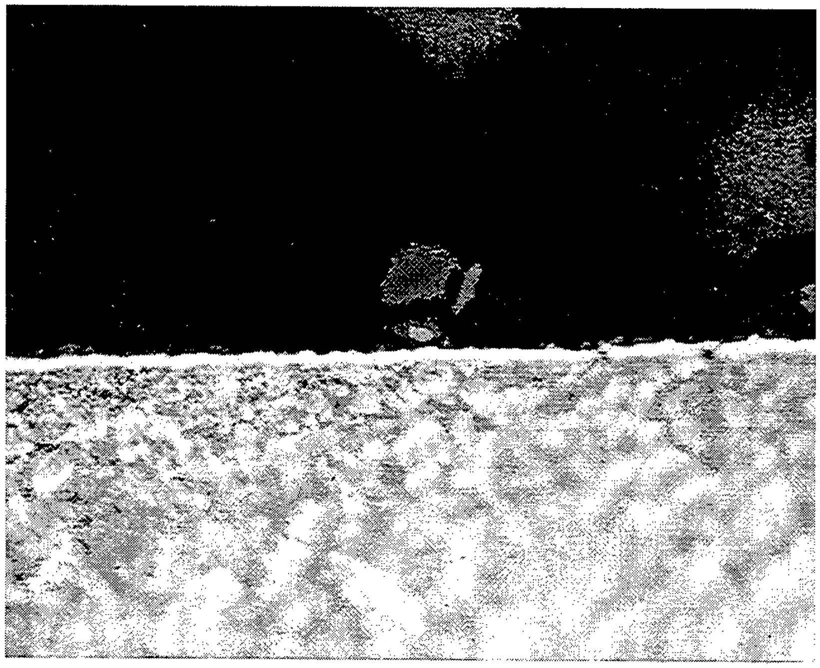
PASSED

SEM examination of the bearing demonstrated that proper nodularity existed in the specimen. **Figures** 86 and 87 show the nodularity at magnifications of 500X and 1000X.

4.2.3.3 Corrosion Testing

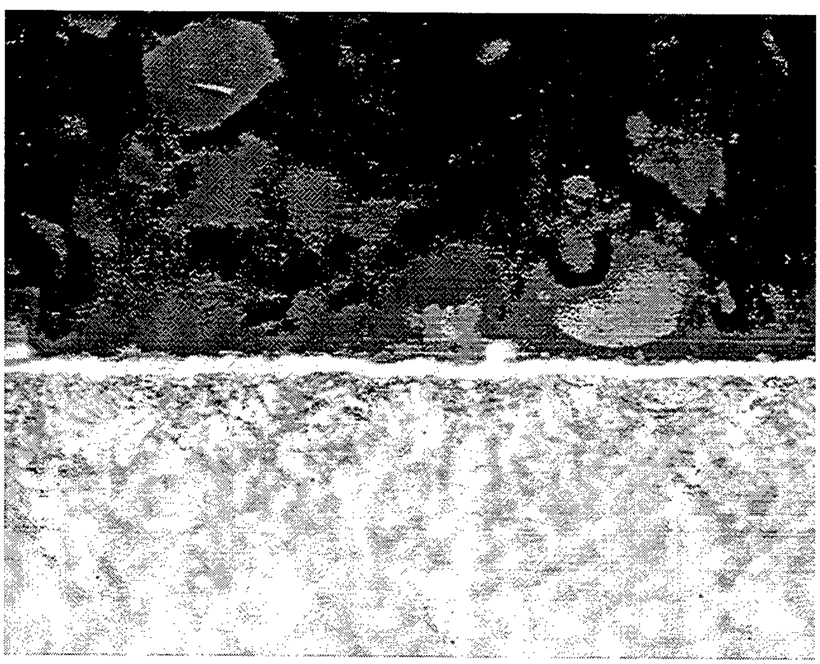
PASSED

Testing was performed at Dirats Laboratories in Westfield, MA. No evidence of corrosion was reported after the 24–hour salt spray testing. The certification of this testing is included in Appendix C.



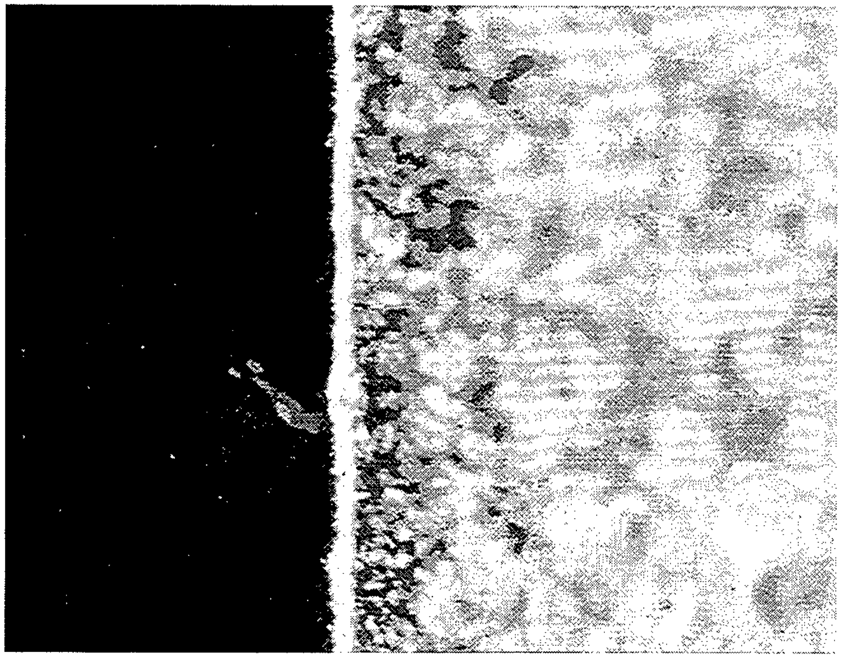
1000X

Figure 75. Optical Photomicrograph of TDC Layer on Raceway of Inner Ring, 65 μin Thick.
Met specification.



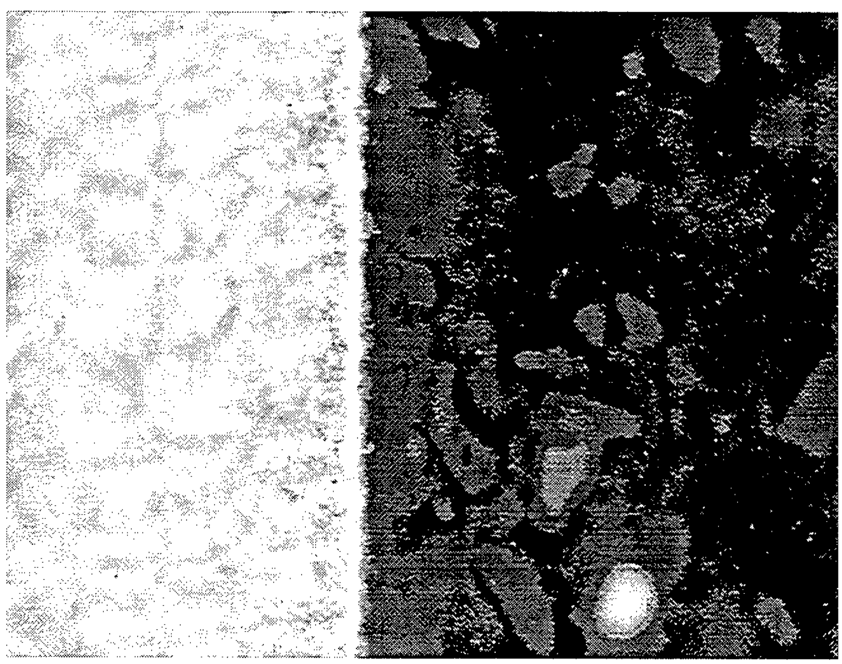
1000X

Figure 76. Optical Photomicrograph of TDC Layer on Land of Inner Ring, 80 μin Thick.
Met specification.



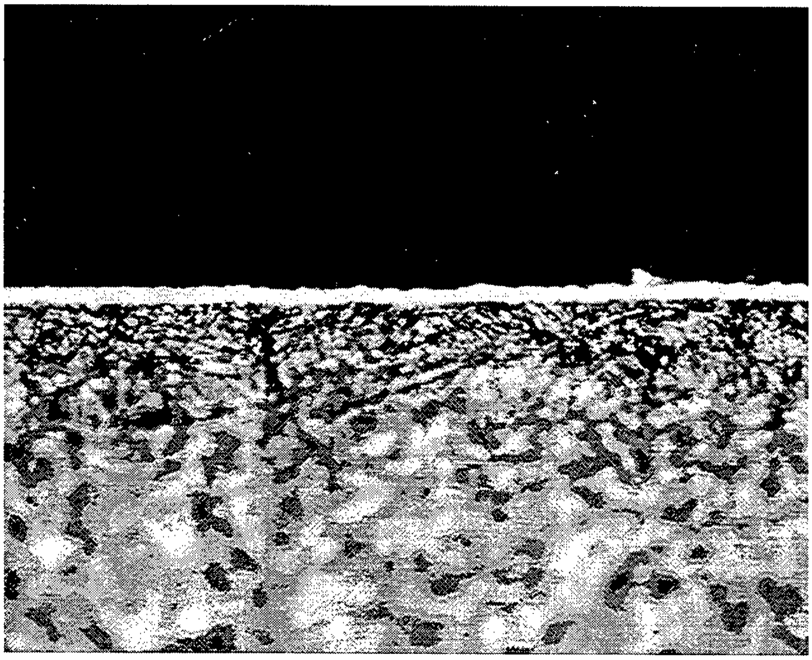
1000X

Figure 77. **Optical Photomicrograph of TDC Layer on Face of Inner Ring, 105 µin Thick.**
Met specification.



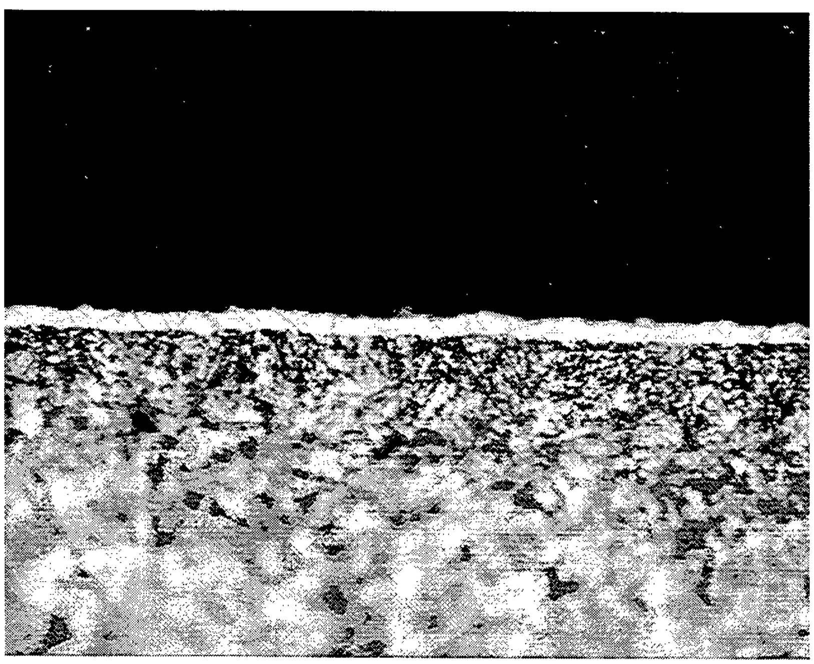
1000X

Figure 78. **Optical Photomicrograph of TDC Layer on Face of Inner Ring, 95 µin Thick.**
Met specification.



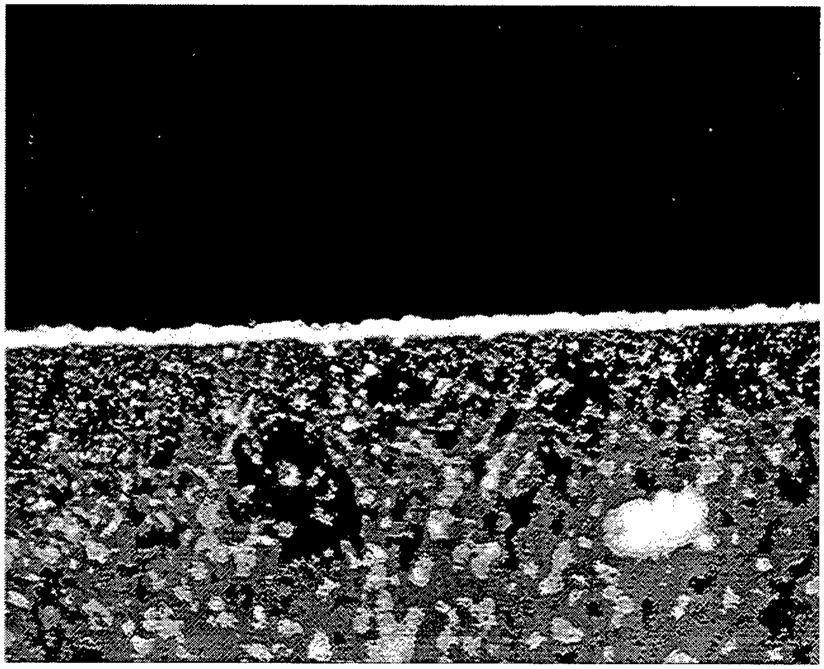
1000X

Figure 79. Optical Photomicrograph of TDC Layer on Bore of Inner Ring, 90 µin Thick. *Met specification.*



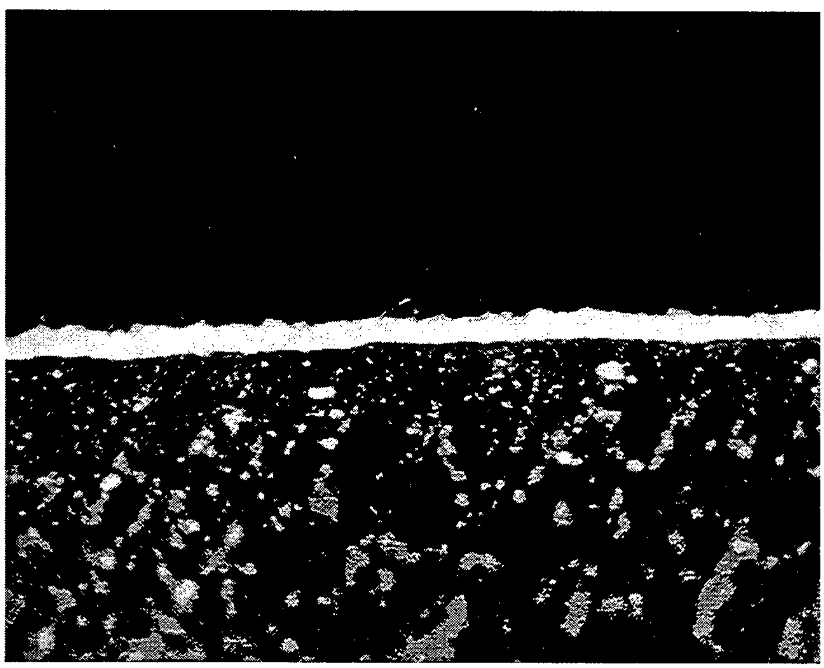
1000X

Figure 80. Optical Photomicrograph of TDC Layer on Bore of Inner Ring, 100 µin Thick. *Met specification.*



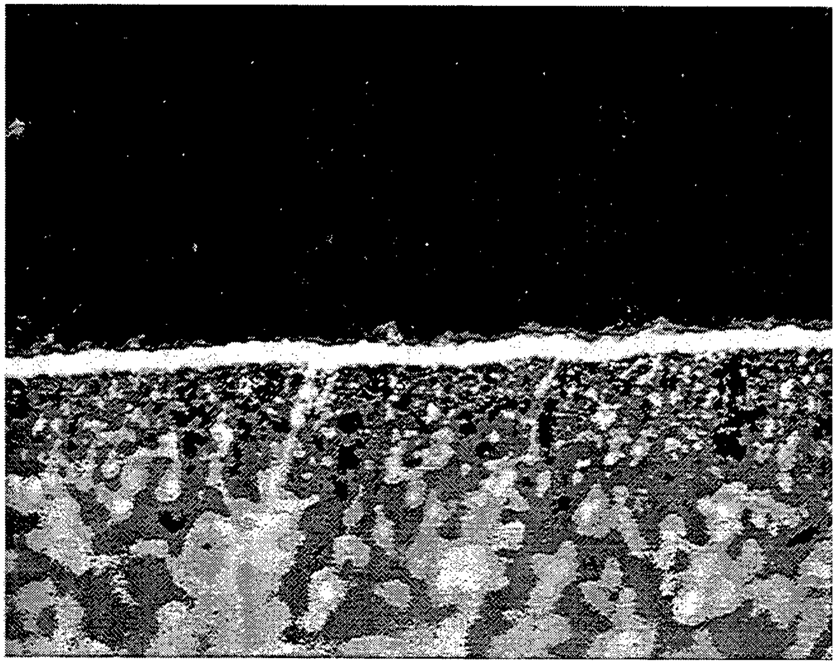
1000X

Figure 81. **Optical Photomicrograph of TDC Layer on Raceway of Outer Ring, 85 μin Thick.**
Met specification.



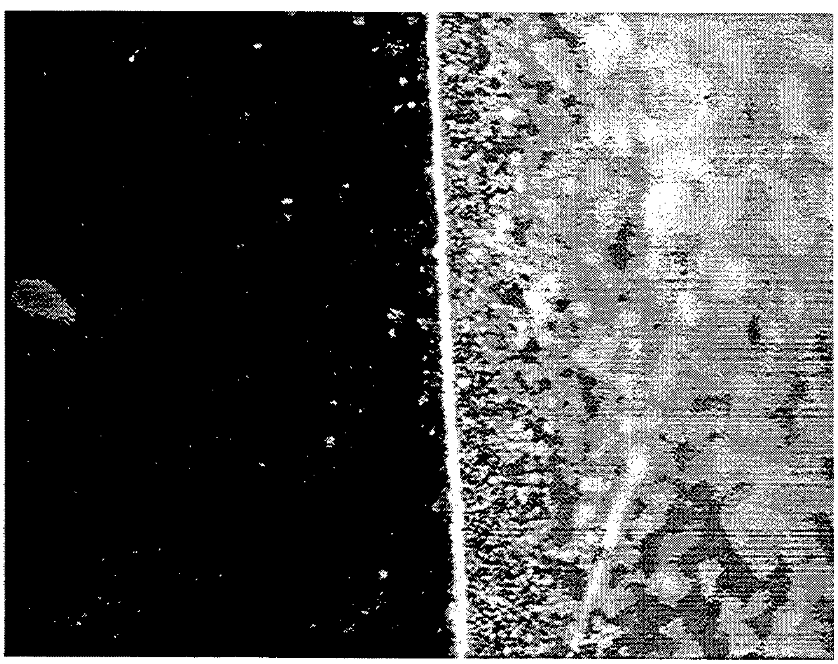
1000X

Figure 82. **Optical Photomicrograph of TDC Layer on Land of Outer Ring, 140 μin Thick.**
Met specification.



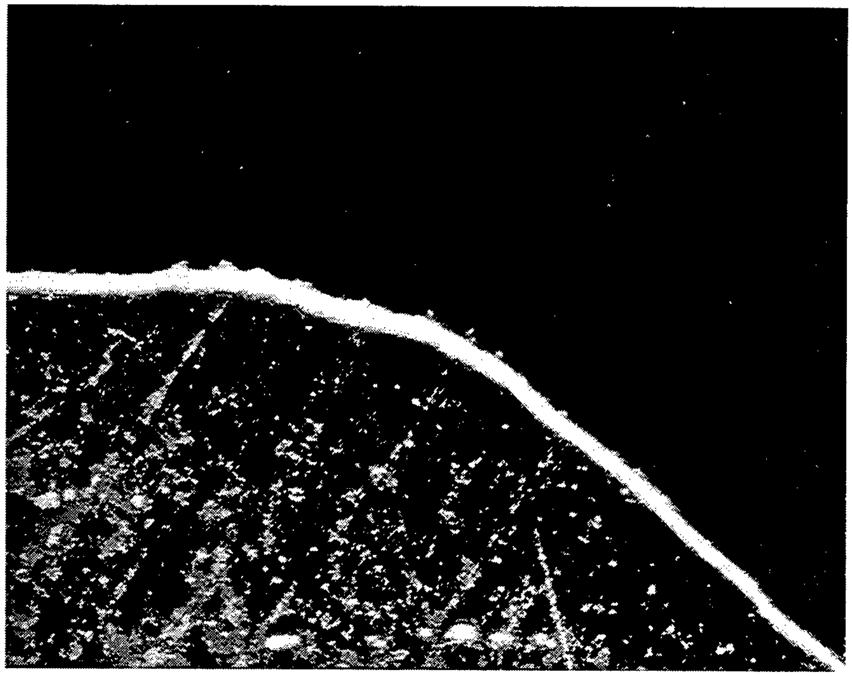
1000X

Figure 83. Optical Photomicrograph of TDC Layer on Outer Diameter of Outer Ring, 100 μin Thick.
Met specification.



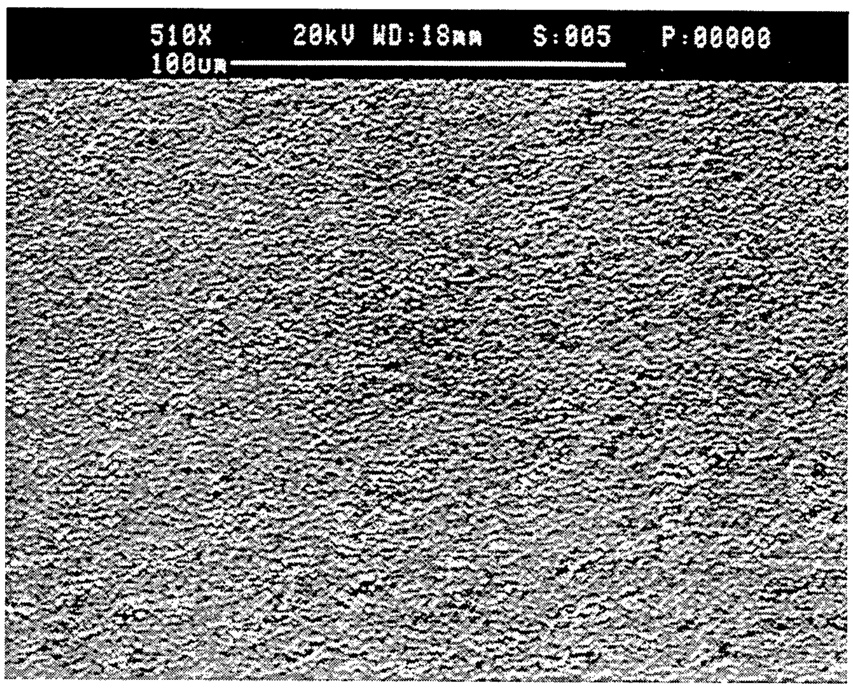
1000X

Figure 84. Optical Photomicrograph of TDC Layer on Face of Outer Ring, 60 μin Thick.
Met specification.



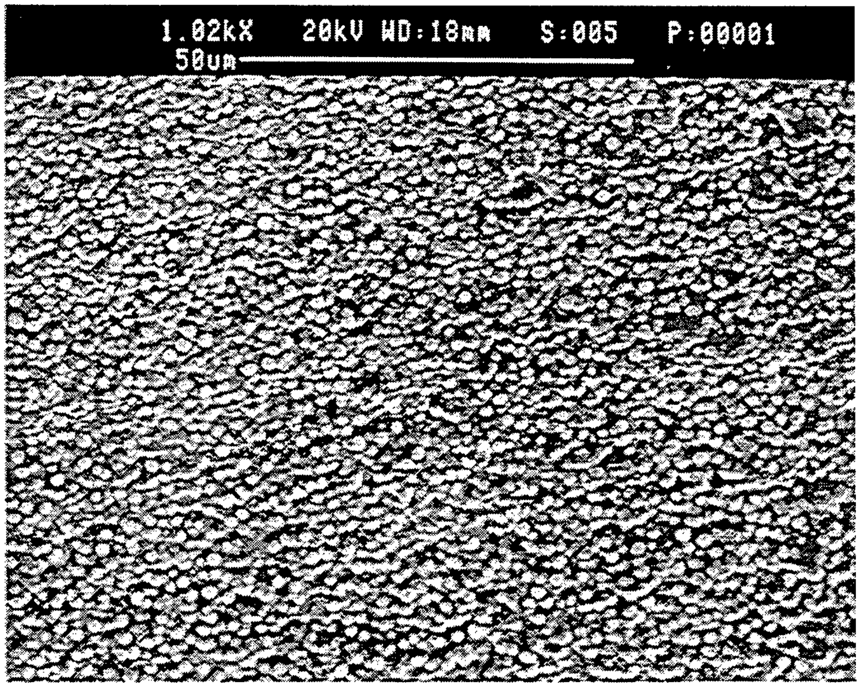
1000X

Figure 85. Optical Photomicrograph of TDC Layer on Corner of Outer Ring, 220 μin Thick. *Met specification.*



500X

Figure 86. SEM Photomicrograph of TDC Surface. *Fine nodularity met specification.*



1000X

Figure 87. SEM Photomicrograph of TDC Surface. *Fine nodularity met specification.*

4.2.3.4 Hydrogen Embrittlement

PASSED

All three of the TDC samples were suspended after surviving 200 hours at 75% of the ultimate tensile strength for M50.

4.2.3.5 Wear Testing

PASSED

Taber wear testing indicated an average wear of 1.7mg/5,000 cycles. This results in a wear index of 0.3, which is well below the specification maximum of 1.2. The certification of this testing is included in Appendix C.

4.2.3.6 Adhesion Testing

PASSED

The TDC coating passed the AMS 2438 Par. 3.3.3, which specifies no separation is allowed from the base metal after repeated bending through an angle of 180 degrees on a diameter equal to the thickness of the test specimen.

4.2.3.7 Thermal Shock Testing

PASSED

Two TDC plated rings were subjected to the 10 thermal cycles. No cracking or peeling was evident when examined at 15X and 500X.

4.2.3.8 Residual Stress

PASSED

Residual stress analysis indicated that the TDC was in a state of residual compressive stress, as required.

4.2.3.9 Rolling Contact Fatigue

FAILED

Rolling contact fatigue testing was performed on 24 baseline (unplated) and 24 TDC plated 5HTH 207 bearings. There were six groups of four bearings and the sudden death method of

rolling contact fatigue testing was used. The operating conditions were as follows: 3,350 pound thrust load resulting in a 406 ksi contact stress, 5,400 RPM, Exxon Turbo MIL–L–7808 oil, with oil inlet temperature of 160°F, filtered through a three micron oil filter, and 2,500 hour suspension. In an attempt to get a few more failures two sets from both the baseline and the TDC coated groups were allowed to run beyond the 2,500 hour suspension mark. Accelerometers were used to detect the onset of bearing spalling, which automatically shut down the test rig. A schematic of the test rig is shown in **Figure** 88.

Two baseline (bare M50) failures occurred, one at 620 hours and the other at 4,030 hours. Five TDC coated bearings failed at 41, 225, 1,825, 2,293, and 2,710 hours. All failures were inner ring spalls. The estimated L10 calculation for the population based on this experiment was 2,943 hours for the baseline bearings and 519 hours for the TDC coated bearings. The TDC coated bearings L10 life clearly appeared inferior in RCF to the unplated baseline bearings. **Figures** 89 through 95 show both the failed baseline and TDC coated inner rings from this round of testing.

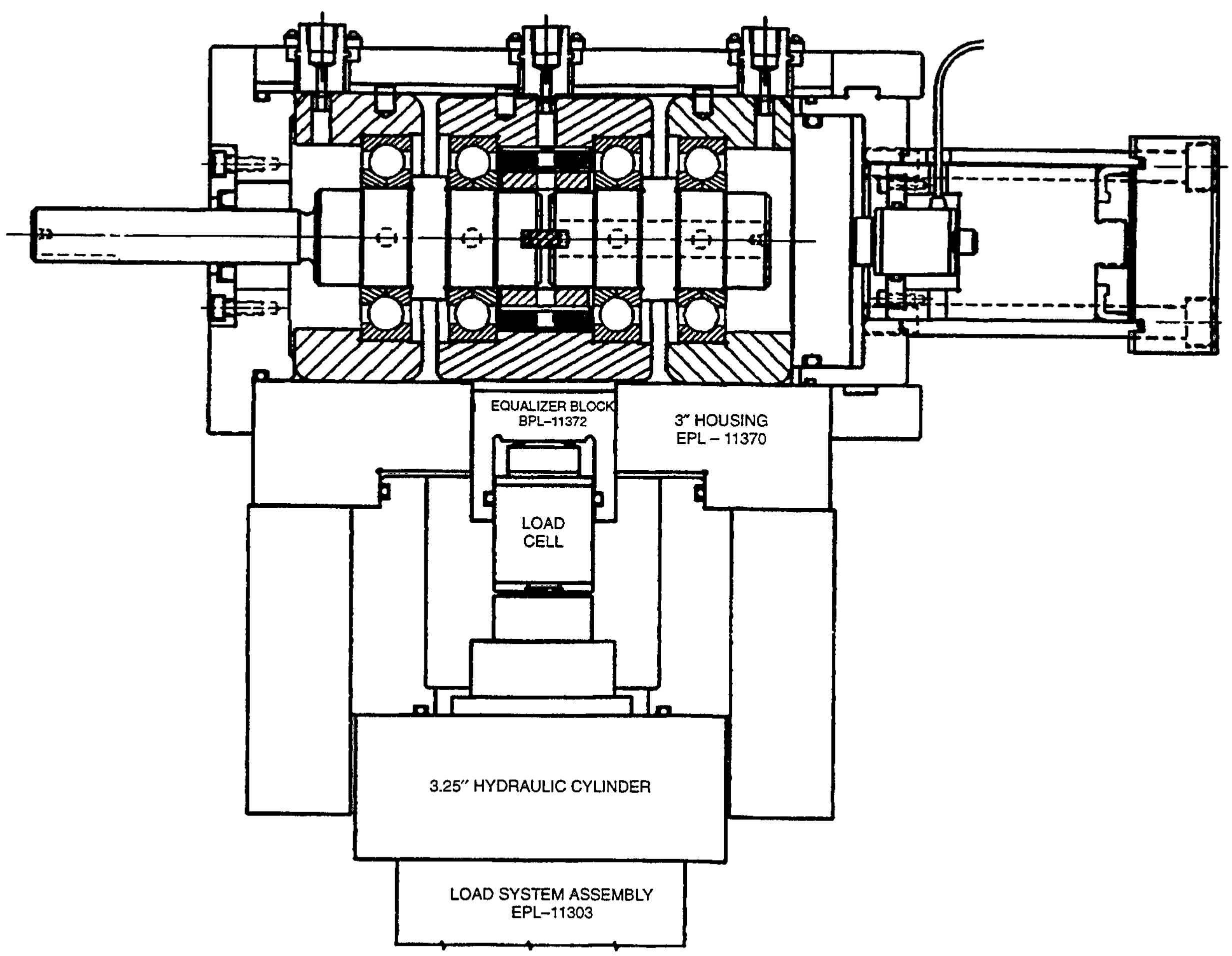


Figure 88. Schematic of the Endurance Testing Bearing Test Rig.

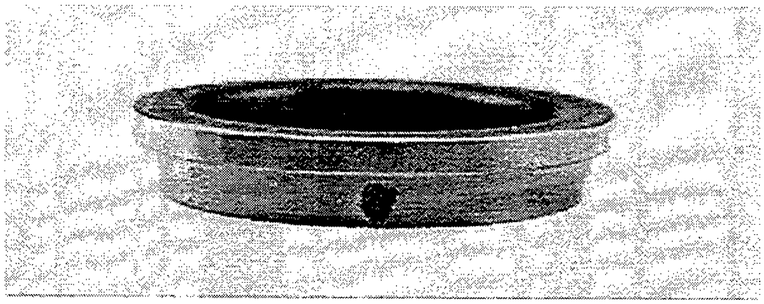


Figure 89. Photo of Plain Bearing Spall Which Failed at 619 Hours.
Only plain bearing to fail within 2,500 hours.

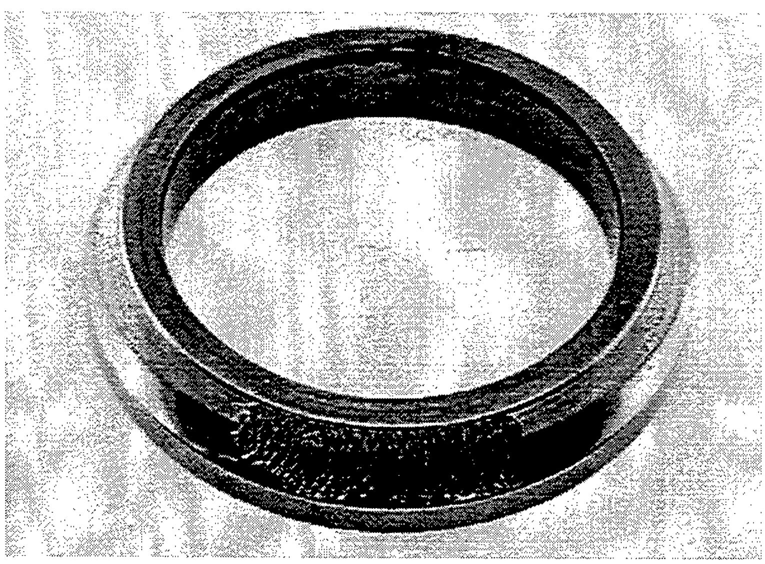


Figure 90. Photo of Plain Bearing Spall Which Failed at 4,030 Hours.

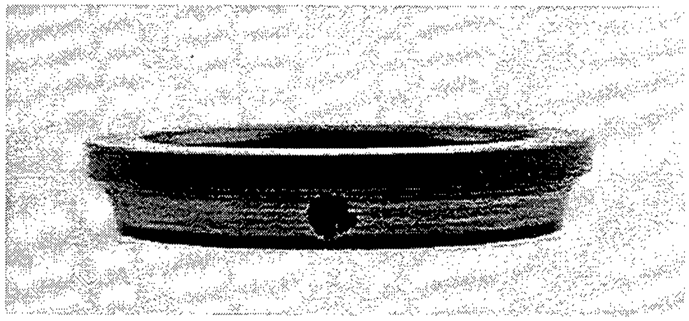


Figure 91. Photo of TDC Coated Bearing Spall Which Failed at 41 Hours.
One of five failures.

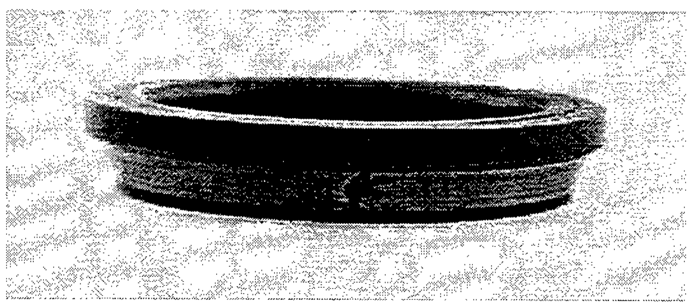


Figure 92. Photo of TDC Coated Bearing Spall Which Failed at 1,825 Hours.
One of five failures.

Surface roughness measurements of the inner race ball track indicated its preplate roughness was approximately 2.0 μin, while its roughness postplating was on the order of 4–5 μin. This corresponded to an initial Lambda around 1.2 to 1.8 for the plain bearings, and around 0.7 for the TDC coated bearing. As in the MRC bearings, this explains why the ball track in the plain bearings was so difficult to see, while they are quite easily found in the TDC coated bearings. Again, it is generally accepted that the fatigue life difference between a bearing with a Lambda of less than 1.0 and one in which it is greater than 1.5 can be very substantial, since the low Lambda ratio bearing is much more prone to surface distress which can lead to early fatigue.

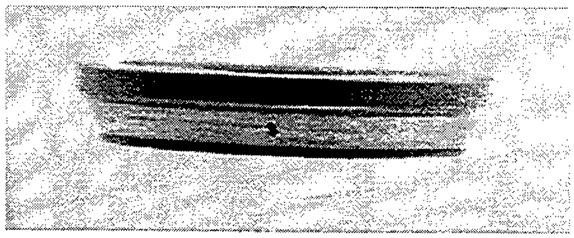


Figure 93. Photo of TDC Coated Bearing Spall Which Failed at 225 Hours.
One of five failures.

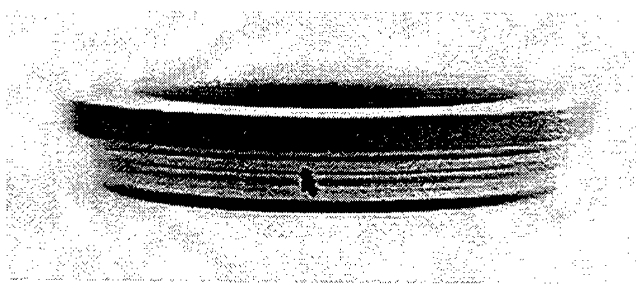


Figure 94. Photo of TDC Coated Bearing Spall Which Failed at 2,710 Hours.
Only TDC failure over 2,500 hours.

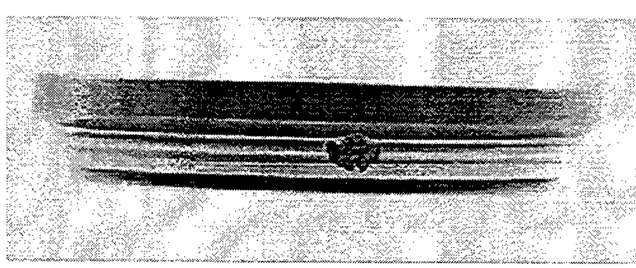


Figure 95. Photo of TDC Coated Bearing Spall Which Failed at 2,293 Hours.
One of five failures. Note easy to see ball track. The L10 of the TDC coated bearing was 1/6th that of the bare bearings.

One area of the test procedure that was changed in the second round of testing was the loading rate. In the first round of testing it took seven hours (in a linear manner) to bring the test rig up to full load. The start–up procedure included preloading the bearing from 5 to 10% of the final full load, bringing the rig up to full speed over a period of roughly seven hours, and slowly increasing the load until full load was obtained. Some concerns were voiced about the possibility of causing skidding damage early on, when the bearing was at full speed but low load, particularly for the TDC coated bearings. These concerns were further supported with the appearance of what looked like a frosted band in the center of the ball track running circumferentially around the bearing, typical of sliding or skidding damage. This frosted ball track is evident in **Figures** 94 and 95. It was agreed that the loading rate would be much quicker in the second round while all other parameters would be kept the same.

At this point, the TDC was considered to have failed the endurance testing, and no vendor was qualified

4.2.4 SBB Round 2

4.2.4.1 Thickness Checks

FAILED

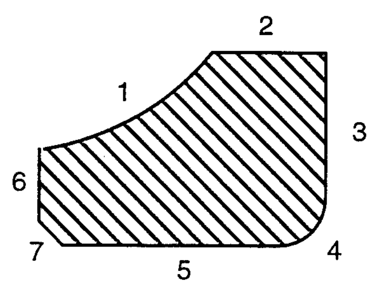
The plating thickness was determined by sectioning one of the rings and optically photographing the TDC coating at seven different locations.

Figures 96 through 104 show the TDC coatings of these seven areas. Note that area number seven, the bore corner, contained TDC with a thickness of 380μin, which is greater than the 250μin maximum allowed in the GE Specification. Examination of **Figure** 104 also shows what appears to be microcracks running through the TDC coating. This condition is not evident in the thinner coating areas.

4.2.4.2 Topography

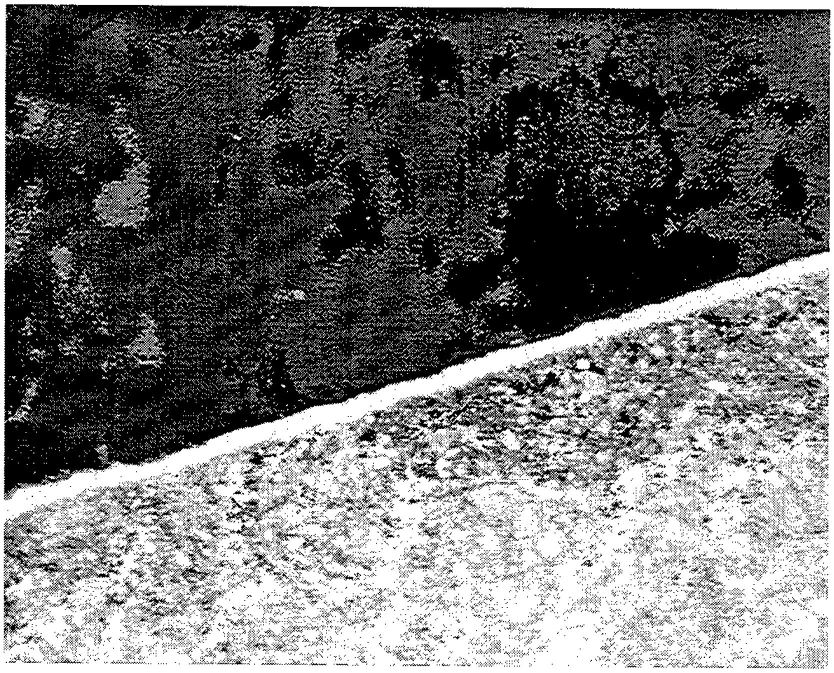
PASSED

Inspection of the functional surface of a sample bearing indicated that it was generally free of cracks, discontinuities, pinholes, or chrome clusters. The nodularity as revealed by SEM



	Area	Thickness (μin)
1	Raceway	100
2	Shoulder	125
3	Face (wide)	75
4	Corner (bore)	150
5	Bore	125
6	Face (narrow)	130
7	Corner (bore)	380 / too thick

Figure 96. TDC Plating Thickness Measurements. *Area 7 was the only measurement above the max. spec. thickness of 250 μin.*



1000X

Figure 97. Optical Photomicrograph of Raceway (Area 1) 100 μin TDC Thickness.
Within specification.

inspection at 500X revealed a proper looking nodular texture, as can be seen in **Figures** 105 and 106.

4.2.4.3 Corrosion Testing

FAILED

Corrosion testing was performed by Dirats Laboratories. The test ring exhibited isolated areas of rust spots after the 24–hour salt spray test. Additional testing was performed using an acidified copper sulfate to determine the presence of exposed iron. Areas of the bore to abutting face chamfer (Area 7 in Figure 96) and the shoulder exhibited a copper color after six minutes in the solution, indicating exposed iron. One of the corner areas adjacent to the corroded zone appeared to be delaminated. **Figure** 107 shows the corrosion pits as a result of the salt spray test. Appendix D contains a certification report of this test.

4.2.4.4 Hydrogen Embrittlement

PASSED

Two test bars exceeded the 200 hour load requirement at 75% of the average ultimate notch tensile strength of M50.

4.2.4.5 Wear Testing

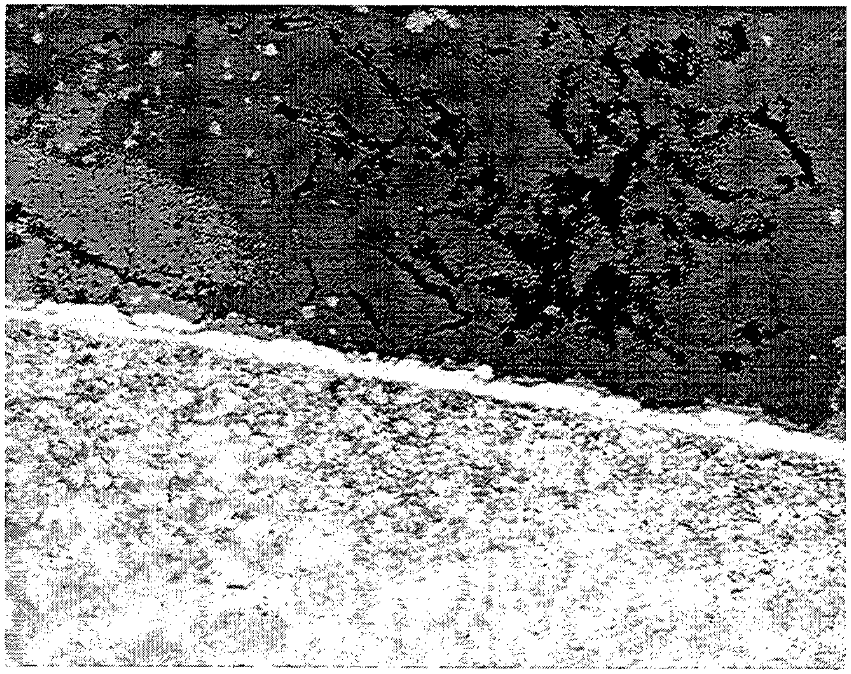
PASSED

Taber wear testing indicated an average wear loss being 5.0mg or a wear index of 1.0 which is less than the specification maximum of 1.2. Appendix **D** contains a certification of this testing.

4.2.4.6 Adhesion Testing

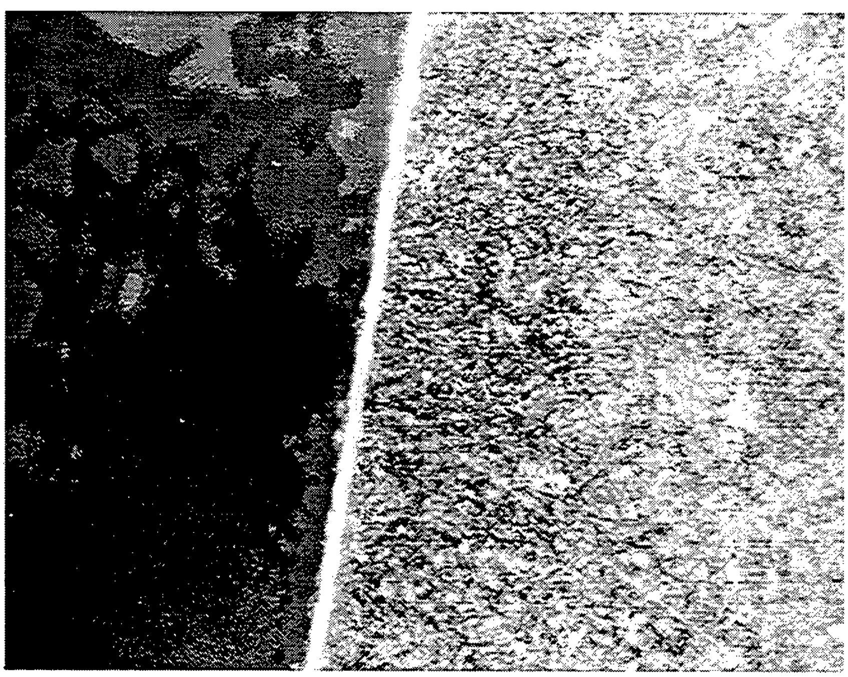
PASSED

Armoloy of CT Inc. conducted this test with no reported failures.



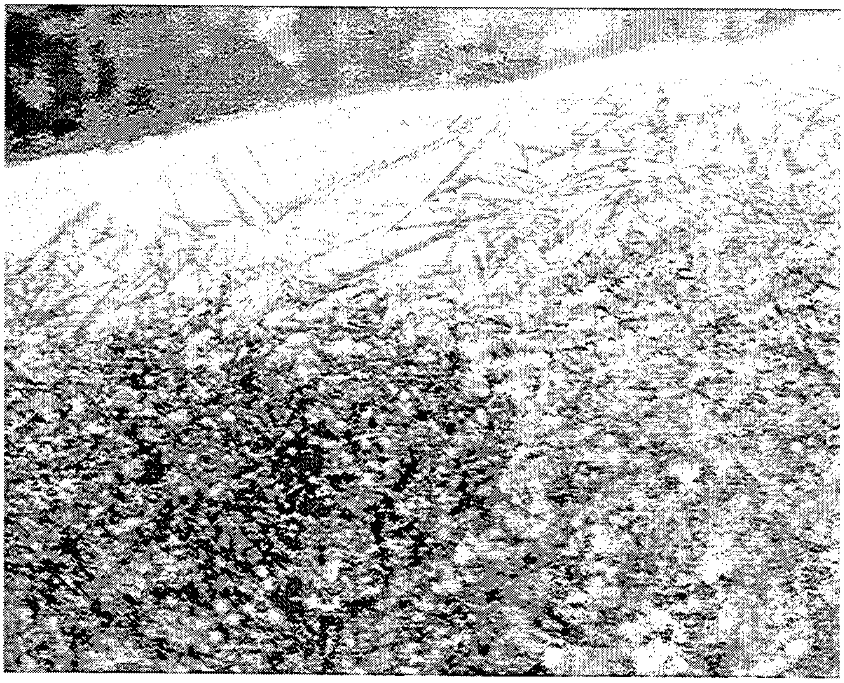
1000X

Figure 98. **Optical Photomicrograph of Shoulder (Area 2) 125 μin TDC Thickness.**
Within specification.



1000X

Figure 99. **Optical Photomicrograph of Wide Face (Area 3) 75 μin TDC Thickness.**
Within specification.

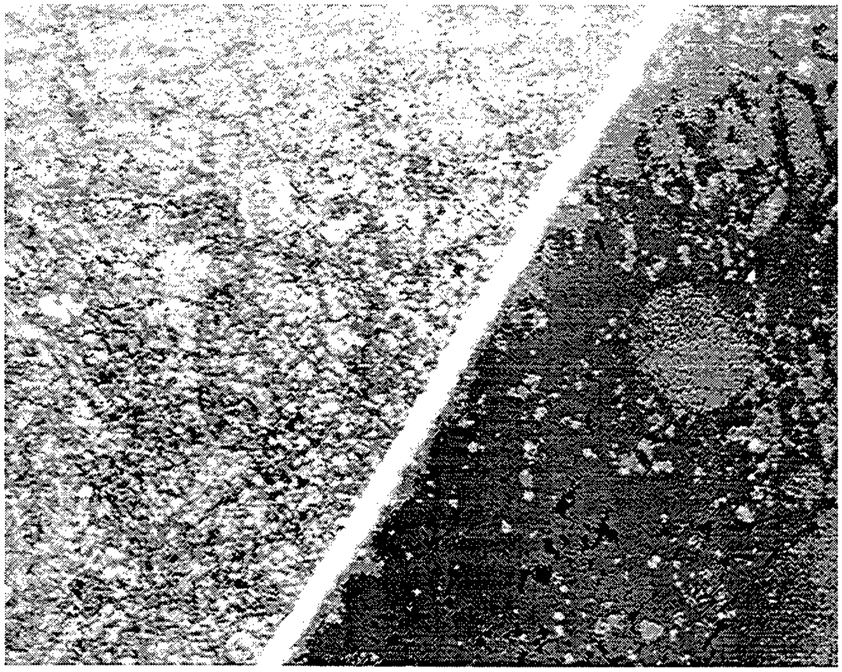


1000X

Figure 100. Optical Photomicrograph of Bore Corner (Area 4) 150 μin TDC Thickness.
Within specification.

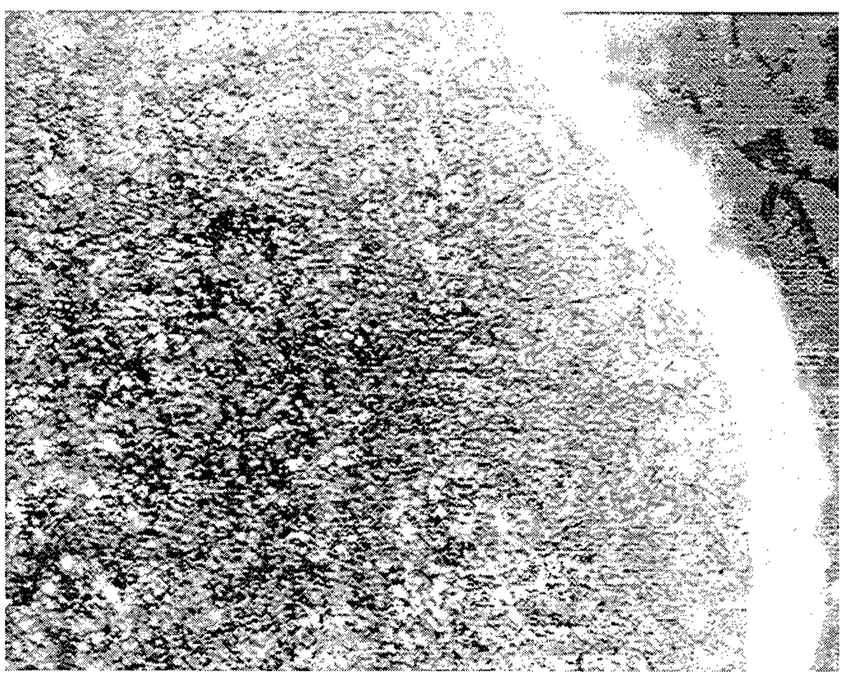
1000X

Figure 101. Optical Photomicrograph of Bore (Area 5) 125 μin TDC Thickness.
Within specification.



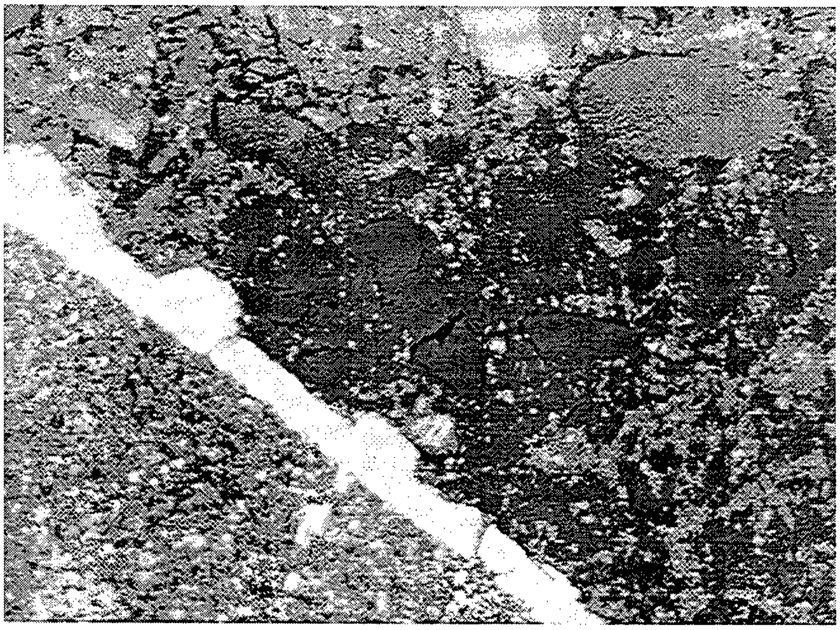
1000X

Figure 102. **Optical Photomicrograph of Narrow Face (Area 6) 130 μin TDC Thickness.**
Within specification.



1000X

Figure 103. **Optical Photomicrograph of Bore Corner (Area 7) 380 μin TDC Thickness.**
Above specification maximum of 250 μin.



1000X

Figure 104. Optical Photomicrograph of Bore Corner (Area 7) 380 μin TDC Thickness.
Above specification maximum of 250 μin, note cracks in TDC plating.

4.2.4.7 Thermal Shock Testing

PASSED

All surfaces examined were found to be crack free after the 10 thermal cycles.

4.2.4.8 Residual Stress

PASSED

Residual stress was measured using a TEC model 1600 x–ray diffraction instrument at SBB. The surface stress of the TDC plated sample was measured as –109 ksi, which meets the residual compressive stress requirement.

4.2.4.9 Rolling Contact Fatigue

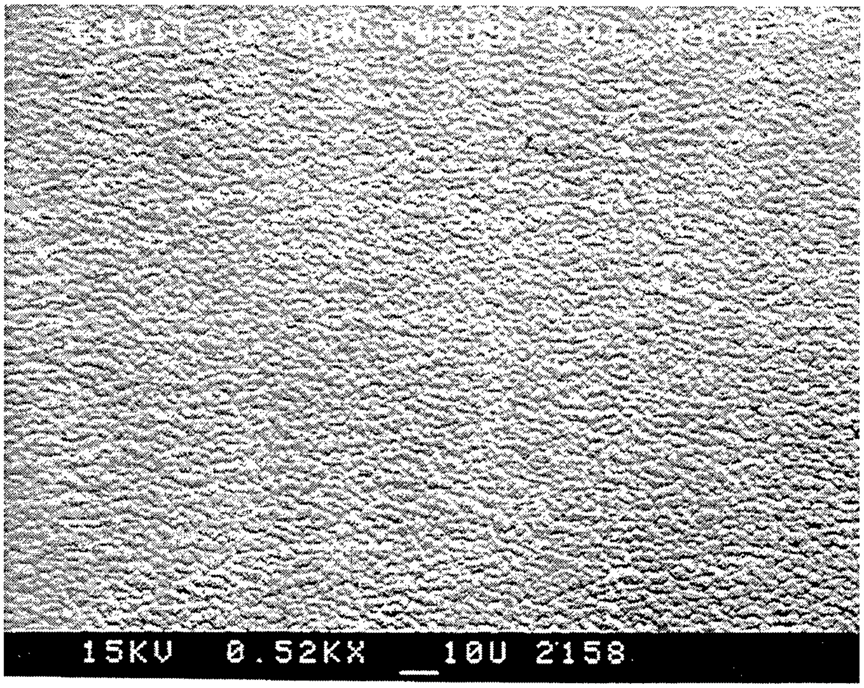
FAILED

Even with the modification to the load application rates, failures of the baked TDC bearings occurred at 246, 501, 710, 1,002, and 1,193 hours, with one group being suspended at 2500 hours. This results in an estimated population L10 life of 595 hours, which is very similar to the L10 of 519 hours exhibited by the TDC coated bearings in Round 1. All of the failures were consistent with Point Surface Originated (PSO) failures, indicating that the TDC coating in a relatively low Lambda bearing may actually degrade the bearings surface integrity and its RCF life.

The TDC plated and unbaked bearing exhibited an even more dramatic reduction in fatigue life. Failures occurred at 28, 40, 196, and 253 hours, with an estimated L10 of 11 hours.

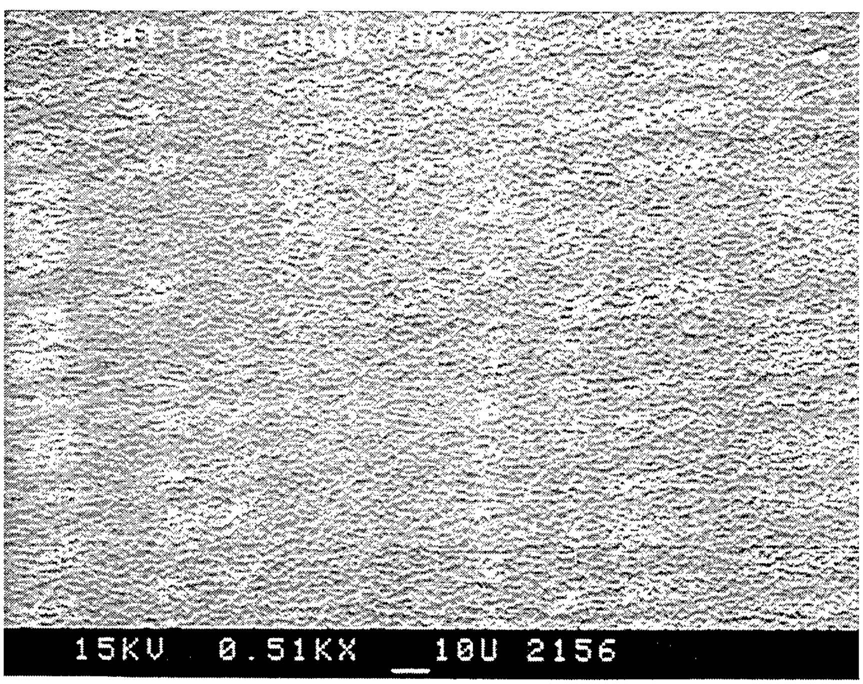
Figures 108 through 112 show the spall failures in the baked TDC plated bearings. SEM examination of the failed bearings revealed that most, if not all, were again surface originated failures. Further examination on the SEM revealed areas just ahead of the spall origination point of distressed TDC, indicated by the white arrows in **Figures** 113 through 115.

The contact ellipse of an angular contact bearing contains elements of rolling, sliding, spinning, and gyroscopic motion. It is the sliding, spinning, and gyroscopic motions which is suspected of causing the TDC distress and subsequent bearing failure, particularly if the Lambda ratio is low.



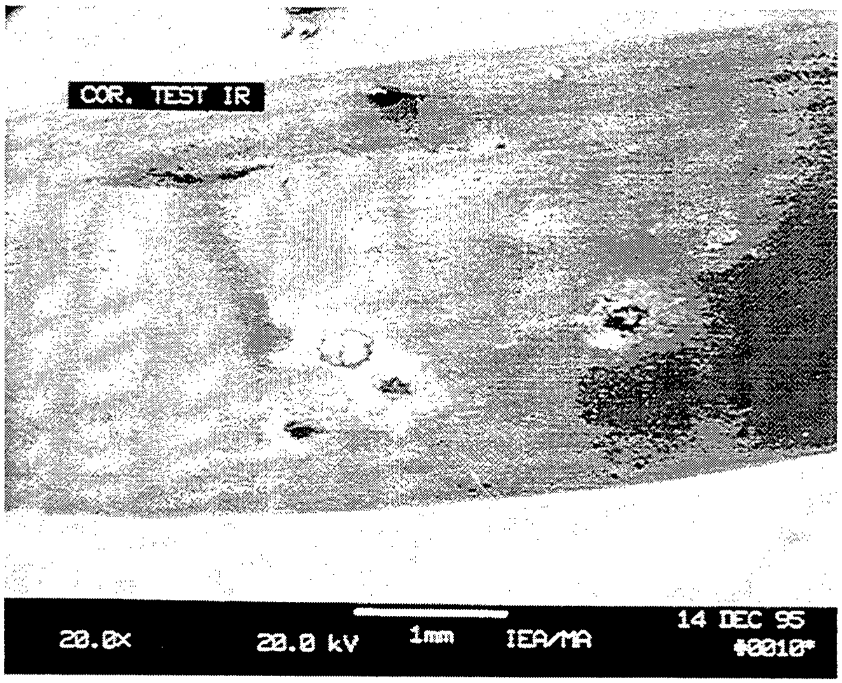
520X

Figure 105. SEM Photomicrograph of the Raceway Bottom Surface Texture.
Within specification.

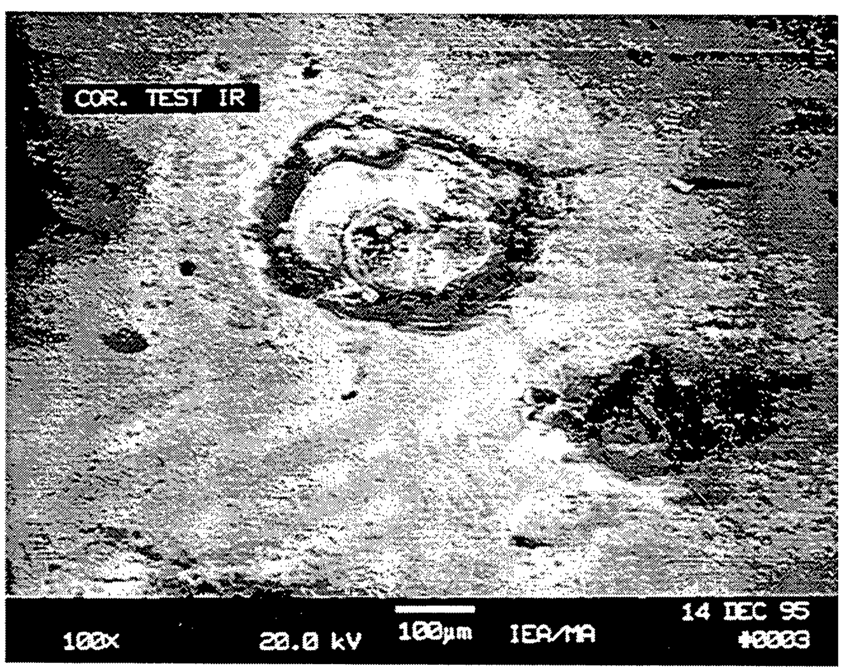


510X

Figure 106. SEM Photomicrograph of the Outside Diameter Surface Texture.
Within specification.

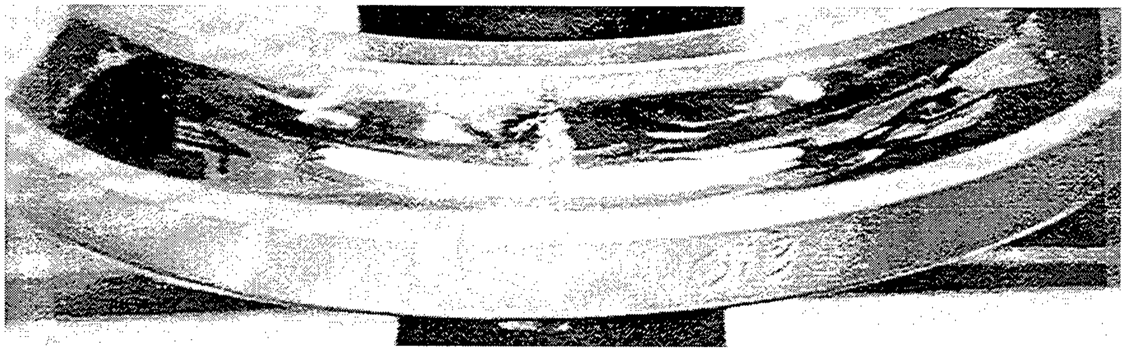


20X



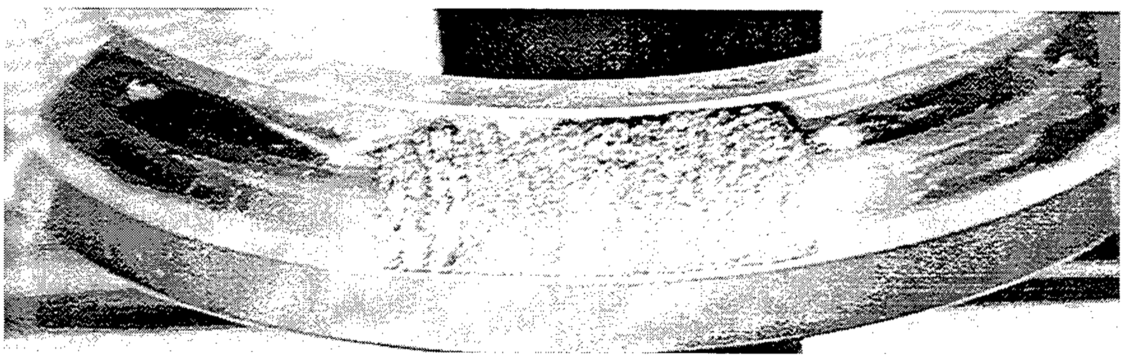
100X

Figure 107. SEM Photomicrographs of Corrosion Test Pits on Bearing Shoulder.
Failed test.



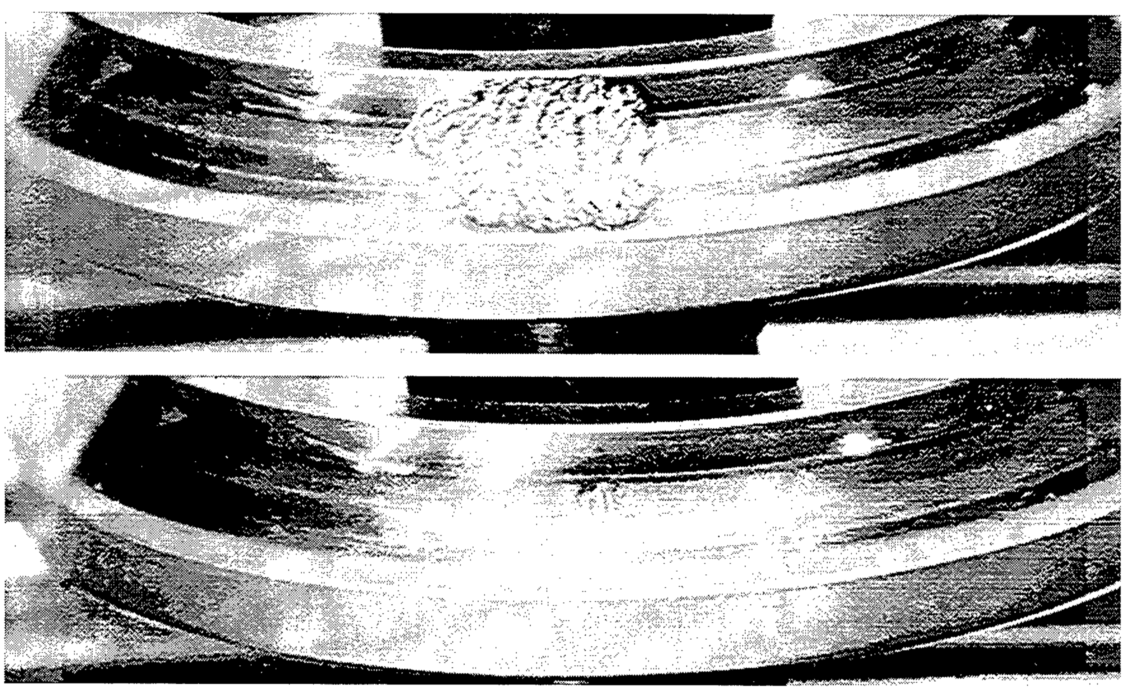
3.5X

Figure 108. Photo of TDC Coated Bearing Spall Failure at 1002.7 Hours.



3.5X

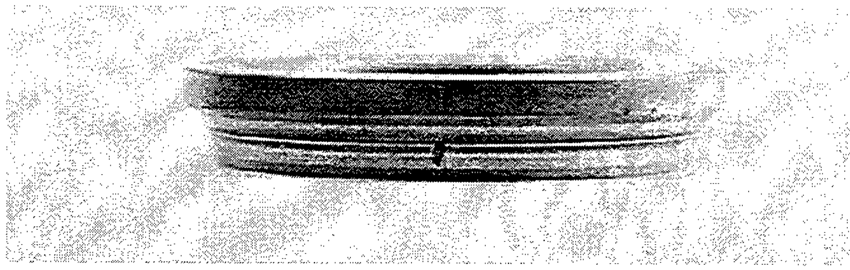
Figure 109. Photo of TDC Coated Bearing Spall Failure at 1193.3 Hours.



3.5X

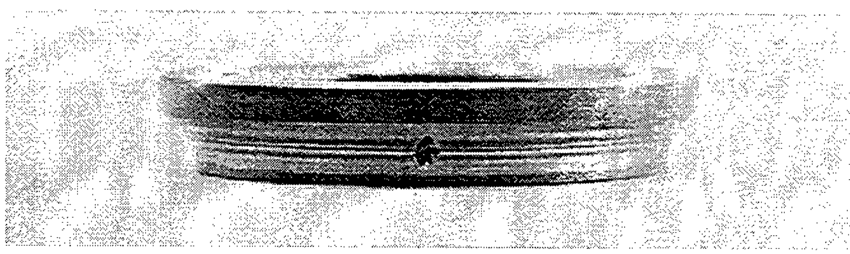
3.5X

Figure 110. Photo of TDC Coated Bearing Spall Failure at 246.6 Hours.
Bearing had both large and small spalls.



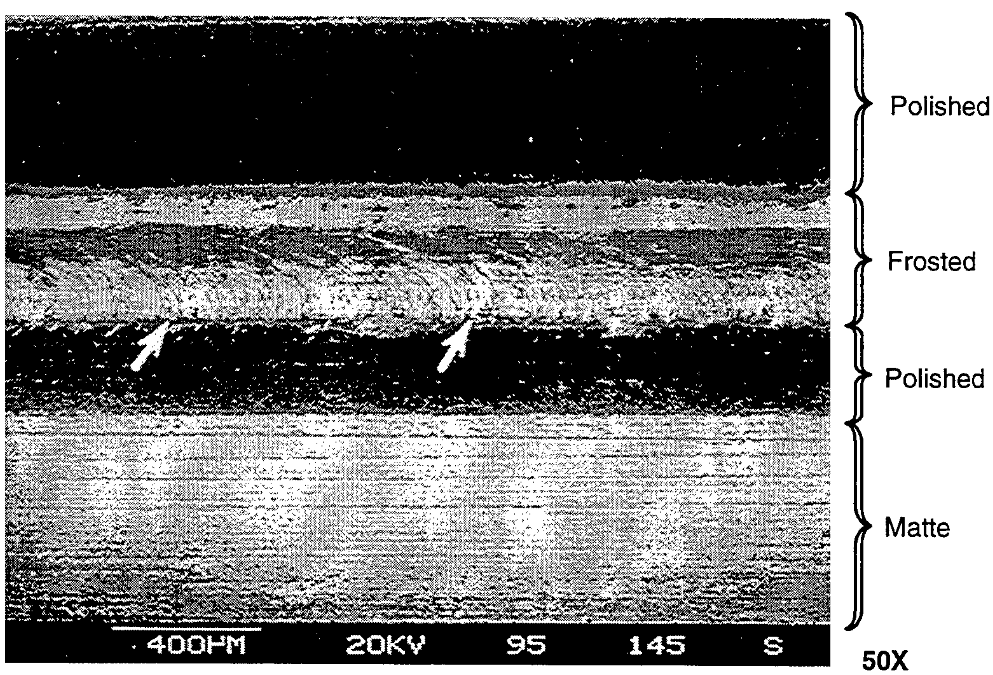
1.5X

Figure 111. Photo of TDC Coated Bearing Spall Failure at 500.8 Hours.



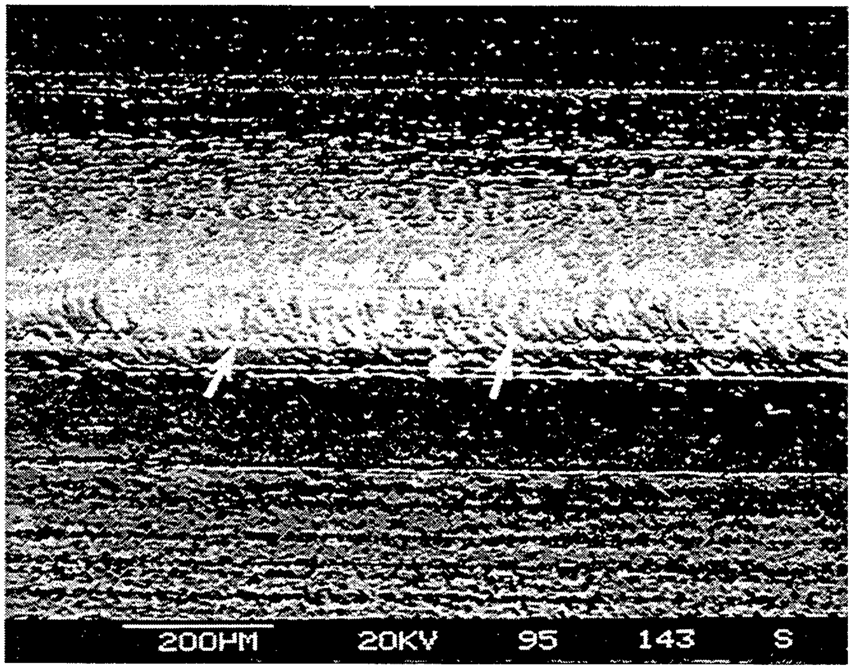
1.5X

Figure 112. Photo of TDC Coated Bearing Spall Failure at 710 Hours.
The L10 of the TDC coated bearings was approximately 1/6th that of the plain bearings. A major concern exists in the application of TDC in low Lambda regions.



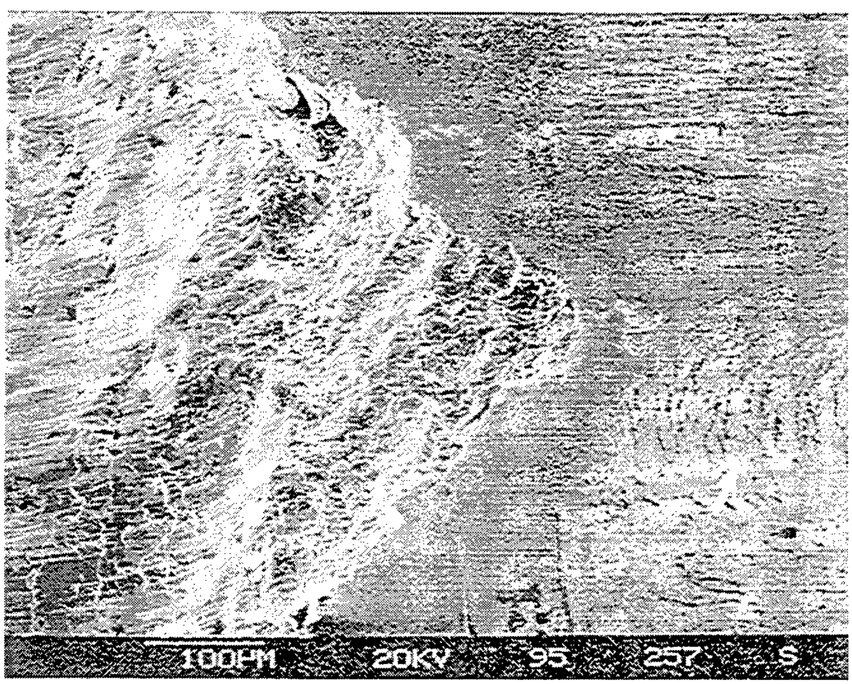
50X

Figure 113. Photomicrograph of Frosted Band in Bearing S/N 0022.
Note distressed TDC from sliding ball in ball track (arrows).



100X

Figure 114. Photomicrograph of Frosted Band in Bearing S/N 0025.
Note sliding type damage in ball track (arrows).



160X

Figure 115. Photomicrograph of S/N 0027 Inner Race Showing Distressed TDC Ahead of Point Surface Originated Spall.

Tables 14 through 18 contain the rolling contact fatigue results for the baseline and TDC plated bearings, as well as the Weibull analysis for the plain and baked TDC RCF results. Appendix D contains the Weibull parameter estimations for the baseline M50, Round 1 and 2 of the TDC plated M50, and the TDC plated unbaked M50 rolling contact fatigue results.

Table 14. Bearing Lives of Round 1 Plain Bearing Tests.

Bearing Serial No.	Bearing Life, hr	Comments
3	619.8	Inner race spall
21	4030.6	
5 through 16	2500	Suspended
17 through 20	5000	

Table 15. Bearing Lives of Round 1 TDC Coated Bearing Tests.

Bearing Serial No.	Bearing Life, hr	Comments
1	41.5	Inner race spall
12	225.5	
5	1825.4	
17	2293.3	
16	2710.4	
21 through 24	2844.3	Suspended

Table 16. Bearing Lives of Round 2 TDC Coated Bearing Tests.

Bearing Serial No.	Bearing Life, hr	Comments
37	246.6	Inner race spall
18	500.8	
21	710	
30	1002.7	
34	1193.3	
20, 23, 24, 26	2500	Suspended

Table 17. Bearing Lives of Not Baked TDC Coated Bearing Tests. *Note the extremely short lives.*

Bearing Serial No.	Bearing Life, hr	Comments
45	28.6	Inner race spall
44	40	
39	196.1	
27	253.1	

Table 18. Weibull Analysis of Plain and Round 1 and 2 TDC Rolling Contact Fatigue Data. *Note the lower RCF of both Rounds of TDC tests.*

Test Group No.	Weibull Slope	L_{10} Life, hr	90% Lower Confidence Band, hr	90% Upper Confidence Band, hr
Bare	0.8307	2943	1843	14117
TDC No. 1	0.5022	519	167	6949
TDC No. 2	1.5157	594	408	1404

5.0 Full Scale Bearing Qualification Testing

A comprehensive test program was completed to demonstrate the integrity of the TDC coating at various in–service engine operating conditions. Testing included both rig and engine tests that have proven successful in the past in demonstrating acceptable bearing performance margins for full scale release to production and in–service engines.

Actual engine bearing hardware was manufactured with TDC coating. Both M50 and M50Nil bearing material was coated and tested. M50 TDC coated bearings had 4340 silver coated cages and M50Nil TDC coated bearings had phosphate coated 4340 cages.

The completed testing is summarized below and detailed further in follow–on paragraphs:

- Operational Endurance Rig Test
- Contamination Endurance Rig Test
- Oil–Off Test
- Skid Testing
- Induced Defect Testing
- Thermal Cyclic Testing
- Corrosion Resistance Demonstration Test

Appendix F includes a tabulation of the bearings tested during the full scale qualification phase of the program.

5.1 Operational Endurance Rig Tests

PASSED

Operational endurance rig testing was completed to demonstrate the reliability and life of the TDC coating at accelerated, simulated engine operating conditions. TDC coating adhesion, wear, and fatigue life characteristics were evaluated based on these tests. Success criteria was based on inspection requirements defined in F110 engine technical order manuals.

A total of six TDC coated bearings were tested. Four bearings included M50 races and the other two included M50NiL races. All bearings included silver plated cages except for one M50NiL bearing which included a phosphate coated cage.

- Testing was completed at the following conditions:
- Shaft Speed: 14,250 rpm ±250 rpm
- Thrust Load: 18,000lb ±50 lb
- Radial Load: None
- Oil Supply Temperature: 275°F ±5°F
- Outer Race Temperature: 400°F max.

Testing continued for 2,000 hours or until indication of bearing distress was detected. Three tests of two bearings each were completed at these conditions.

All six bearings successfully completed the required 2,000 hour testing. **Table** 19 summarizes the results of this test. Posttest inspection results indicated that the TDC remained intact in the raceway ball tracks. **Figure** 116 illustrates a typical bearing outer race condition after 2,000 hours of testing. No evidence of TDC coating distress was found on any of the bearings during posttest inspections.

The TDC coated bearings successfully completed the operational endurance rig tests based on these results.

5.2 Contamination Endurance Rig Test

PASSED

Contamination testing was completed to demonstrate the resistance of TDC coated bearings to surface damage when exposed to aluminum oxide contaminants. Success criteria was based on comparison of test results of plain (uncoated) and TDC coated bearings. The TDC

Table 19. Operational Endurance Rig Test Results.

SUPPLIER	GE P/N and S/N	RACE/COATING/ CAGE PLATE MATERIALS	TEST TIME (HRS.)
SBB	1665M43P01 MABS9632	M50/TDC/Silver	2,000 (Suspended)
SBB	1665M43P01 MABS9636	M50/TDC/Silver	2,000 (Suspended)
SBB	1665M45P01 MABS6867	M50Nil/TCD/Silver	2,000 (Suspended)
SBB	1665M45P02 MABS6755	M50NiL/TDC/Phosphate	2,000 (Suspended)
MRC	1665M42P01 MDACE702	M50/TCD/Silver	2,000 (Suspended)
MRC	1665M42P01 MDACE703	M50/TDC/Silver	2,000 (Suspended)

coated bearings successfully passed this test when they demonstrated reduced contamination damage compared to plain bearings.

A total of six bearings completed the contamination test. Three TDC coated bearings (two with M50 races and one with M50NiL races) and three plain (uncoated) bearings (two with M50 races and one with an M50NiL race) were tested. All bearings included silver plated cages except for one TDC coated, M50NiL bearing which included a phosphate coated cage.

Testing was completed at the following conditions:

- Shaft Speed: 14,250 rpm ±250 rpm
- Thrust Load: 6,000 lb ±100 lb
- Radial Load: None
- Oil Supply Temperature: 175°F ±5°F
- Outer Race Temperature: 375°F ±25°F
- Oil Contamination: 0.2 gram of Aluminum Oxide, 75 micron size

Three tests of two bearings each were completed at these conditions. Testing continued for 1,000 hours or until bearing distress.

The first test was completed with one TDC coated and one plain M50NiL bearing. Testing was stopped after 96.9 hours due to outer race spalling of the plain bearing. **Figure** 117 is a photograph of the outer race spalling. Condition of the TDC coated bearing was acceptable as illustrated in **Figure** 118.

The second test was completed with two TDC coated M50 bearings. Both bearings successfully completed the required 1,000 hours of testing. Posttest inspection indicated that the TDC remained intact on both bearings. **Figure** 119 illustrates the acceptable condition of the TDC coating after test.

A third test was completed with two plain M50 bearings. Testing was stopped after 126.3 hours due to outer race spalling on one bearing. Several pits were noted on the outer race of the second bearing. **Figure** 120 is a photograph of the outer race spalling on this bearing. **Table** 20 summarizes the results of this test.

The TDC coated bearings demonstrated significant increase in contamination resistance compared to plain bearings.

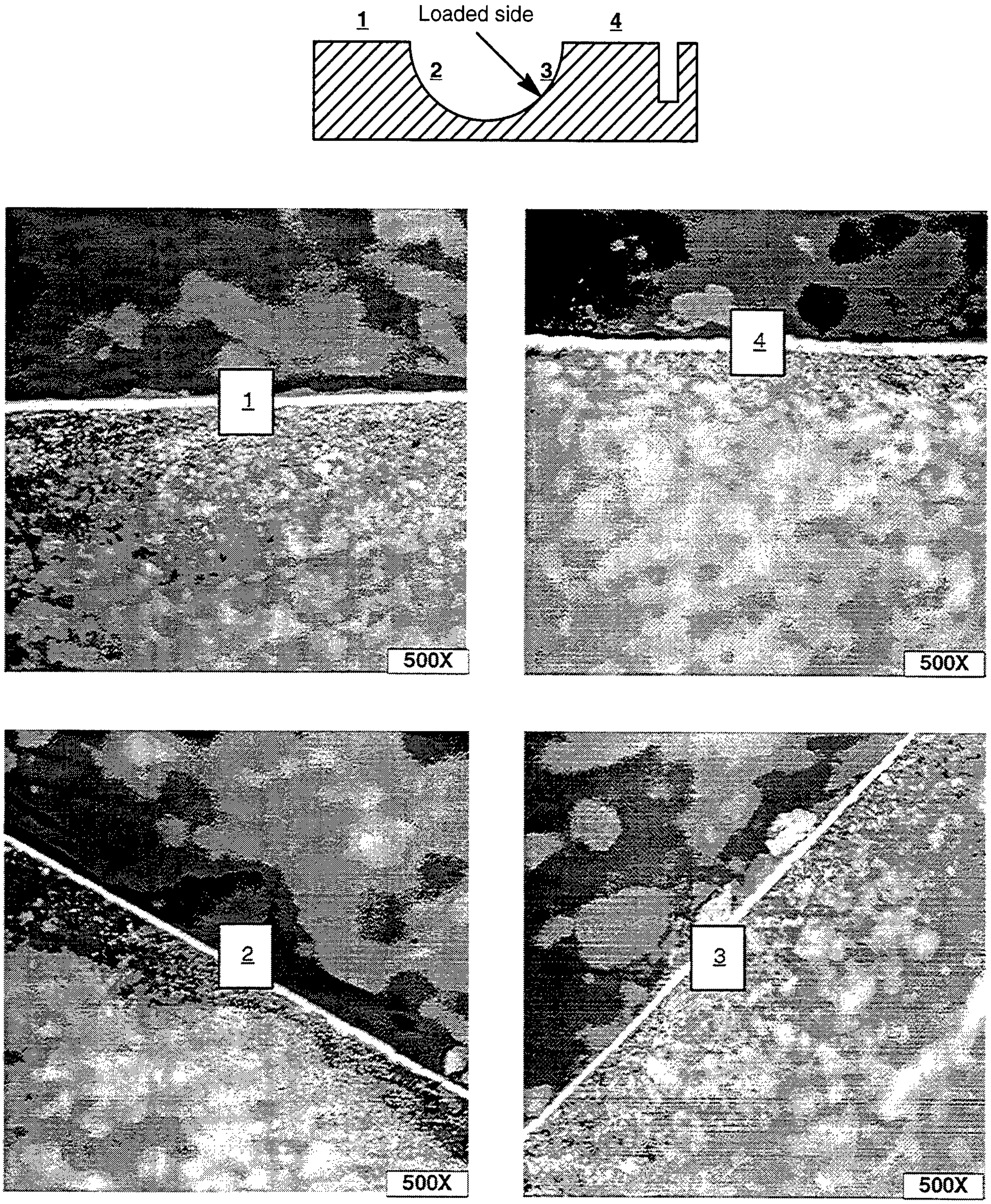


Figure 116. Photos of Bearing S/N MABS9636 After 2,000 Hour Operational Endurance Test.
TDC passed test.

Figure 117. Photo of Outer Race Spalling on Bare, Contamination Tested Bearing.
Bare bearings have significantly less resistance to contamination.

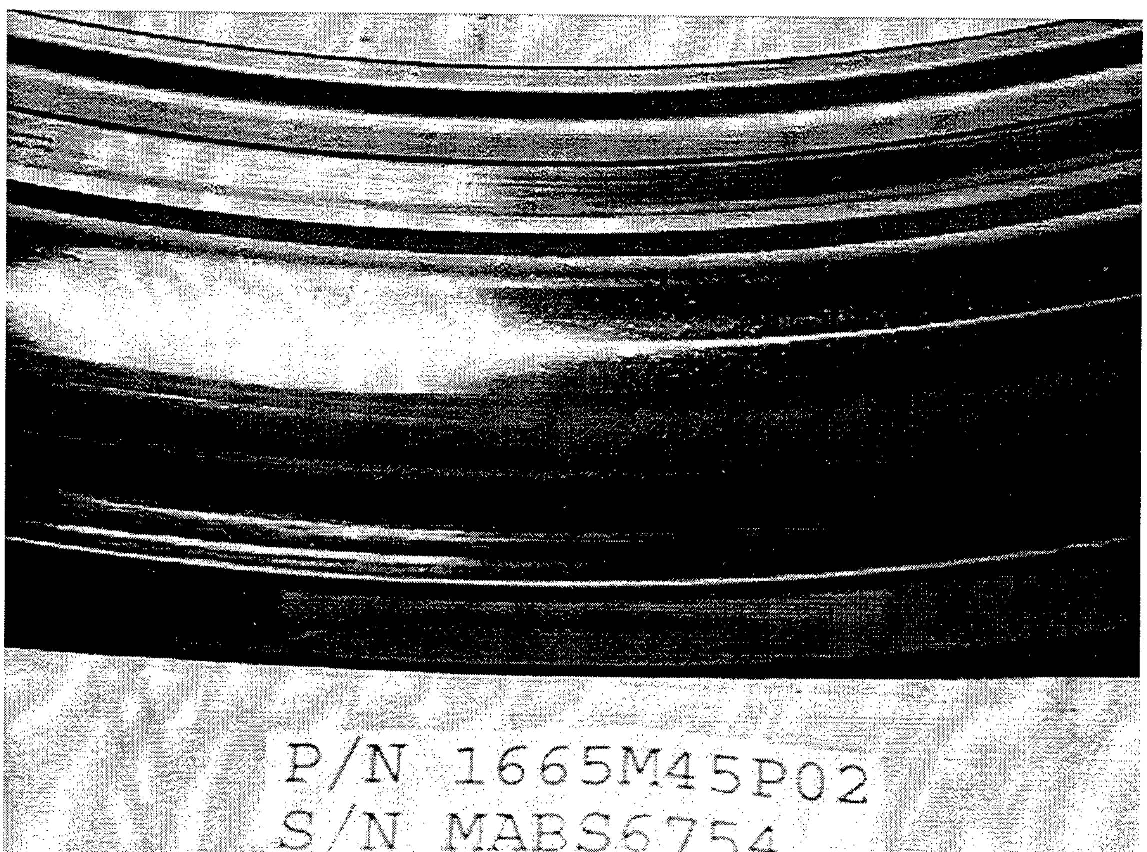


Figure 118. Photo of Contamination Tested TDC Bearing.
TDC coated bearings demonstrated superior contamination resistance.

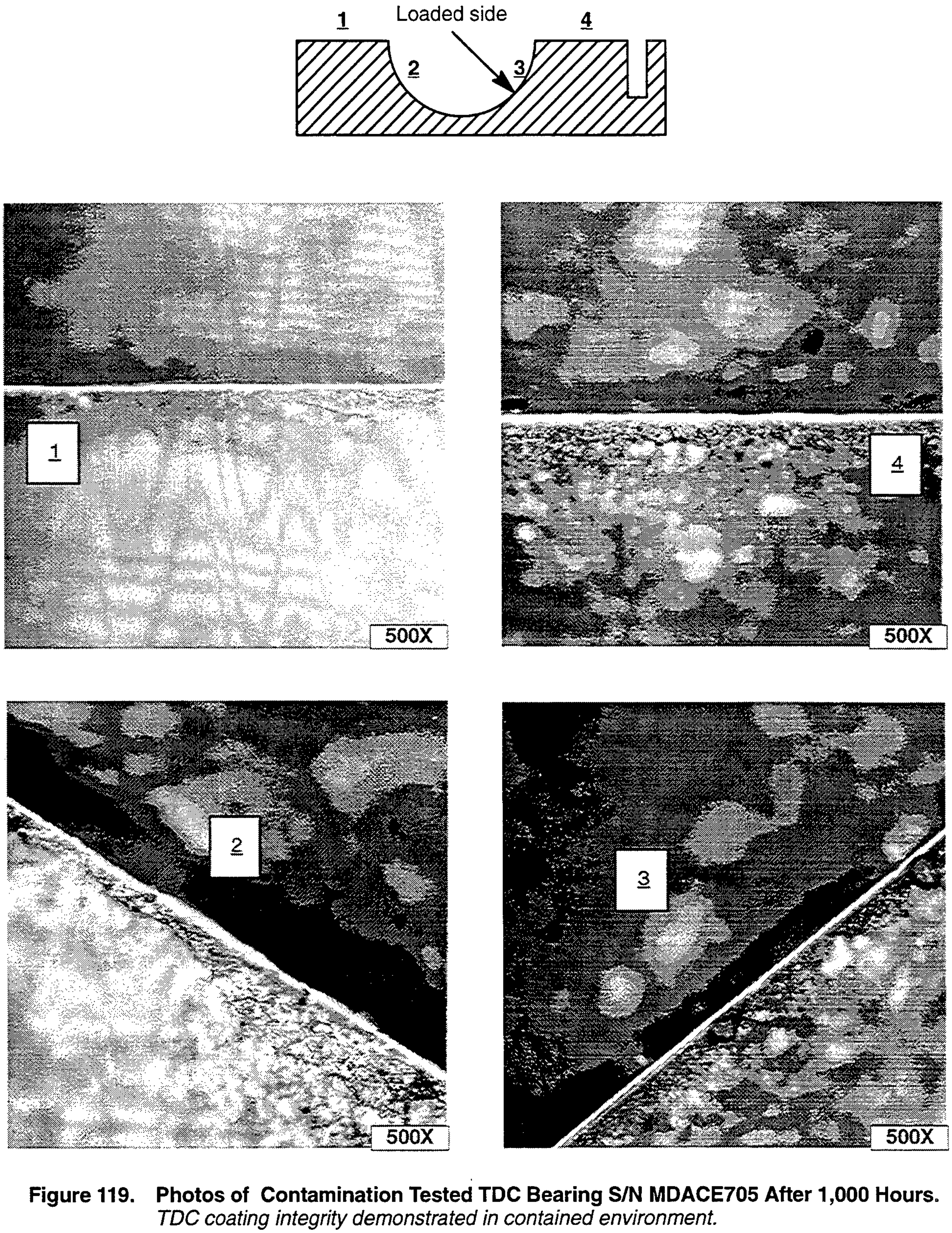


Figure 119. Photos of Contamination Tested TDC Bearing S/N MDACE705 After 1,000 Hours.
TDC coating integrity demonstrated in contained environment.

Figure 120. Photo of Outer Race Spalling on Bare, Contamination Tested Bearing.
Bare bearings repeatedly demonstrated less resistance to contamination.

Table 20. Contamination Endurance Rig Test Results.

SUPPLIER	GE P/N and S/N	RACE/COATING/CAGE PLATE MATERIALS	TEST TIME (HRS.)
SBB	1461M15P06 MABS1887	M50Nil/TiN/Silver	96.9 (O.R. Spalling)
SBB	1665M45P02 MABS6754	M50Nil/TDC/Phosphate	96.9 (Accept)
MRC	1665M42P01 MDACE704	M50/TDC/Silver	1,000 (Suspended)
MRC	1665M42P01 MDACE705	M50/TDC/Silver	1,000 (Suspended)
MRC	9732M10P16 MDA713JV	M50/Silver	126.3 (O.R. Spalling)
MRC	9732M10P16 MDA604JV	M50/Silver	126.3 (O.R. Pitting)

5.3 Oil–Off Tests

PASSED

Oil–off testing was completed to demonstrate TDC coating resistance to distress during simulated conditions of engine oil interruption. The TDC coated bearings were considered to successfully complete this testing if their run times at oil–off conditions were equal to or greater than the test times of plain bearings.

A total of eight bearings completed the oil–off test. Four TDC coated bearings (two each with M50 and M50NiL races) and four uncoated bearings (two each with M50 and M50NiL races) were tested. All bearings included silver plated cages except for one TDC coated, M50NiL bearing which included a phosphate coated cage.

Testing was completed at the following conditions:

- Shaft Speed: 14,900 rpm ±100 rpm
- Thrust Load: 11,500 lb ±50 lb
- Oil Supply Temperature: 210°F ±5°F

After testing stabilized at these conditions, the oil supply was shut off until either the outer race temperature reached 500°F or 2 minutes time elapsed.

Table 21 summarizes the results of this testing. In all cases, the TDC coated bearings operated for a longer time period except for the bearing with a phosphate coated cage.

It is concluded that the phosphate cage coating was the primary contributor to the reduced time due to the lower lubrication characteristics of phosphate coatings compared to silver coatings.

The TDC coating successfully adhered to the base material and did not demonstrate any evidence of distress resulting from oil–off testing. **Figure** 121 is a photograph of a typical TDC coated bearing outer race after testing, illustrating the acceptable condition of the coating.

Table 21. Oil–Off Test Results.

SUPPLIER	GE P/N and S/N	RACE/COATING/ CAGE PLATE MATERIALS	TIME @ OIL-OFF (Minutes:Seconds)
MRC	9732M10P16 MDA606JV	M50/SILVER	1:28.0
MRC	1665M42P01 MDACE694	M50/TDC/SILVER	1:59.8
SBB	1461M15P06 MABS1881	M50NIL/TiN/SILVER	1:23.6
SBB	1665M45P01 MABS6865	M50NiL/TDC/SILVER	1:59.4
MRC	9732M10P16 MDA607JV	M50/SILVER	0:32.0
MRC	1665M42P01 MDACE695	M50/TDC/SILVER	1:30.4
SBB	1461M15P06 MABS1882	M50NiL/TiN/SILVER	0:35.5
SBB	1665M45P02 MABS6751	M50NiL/TDC/PHOSPHATE	0:25.7

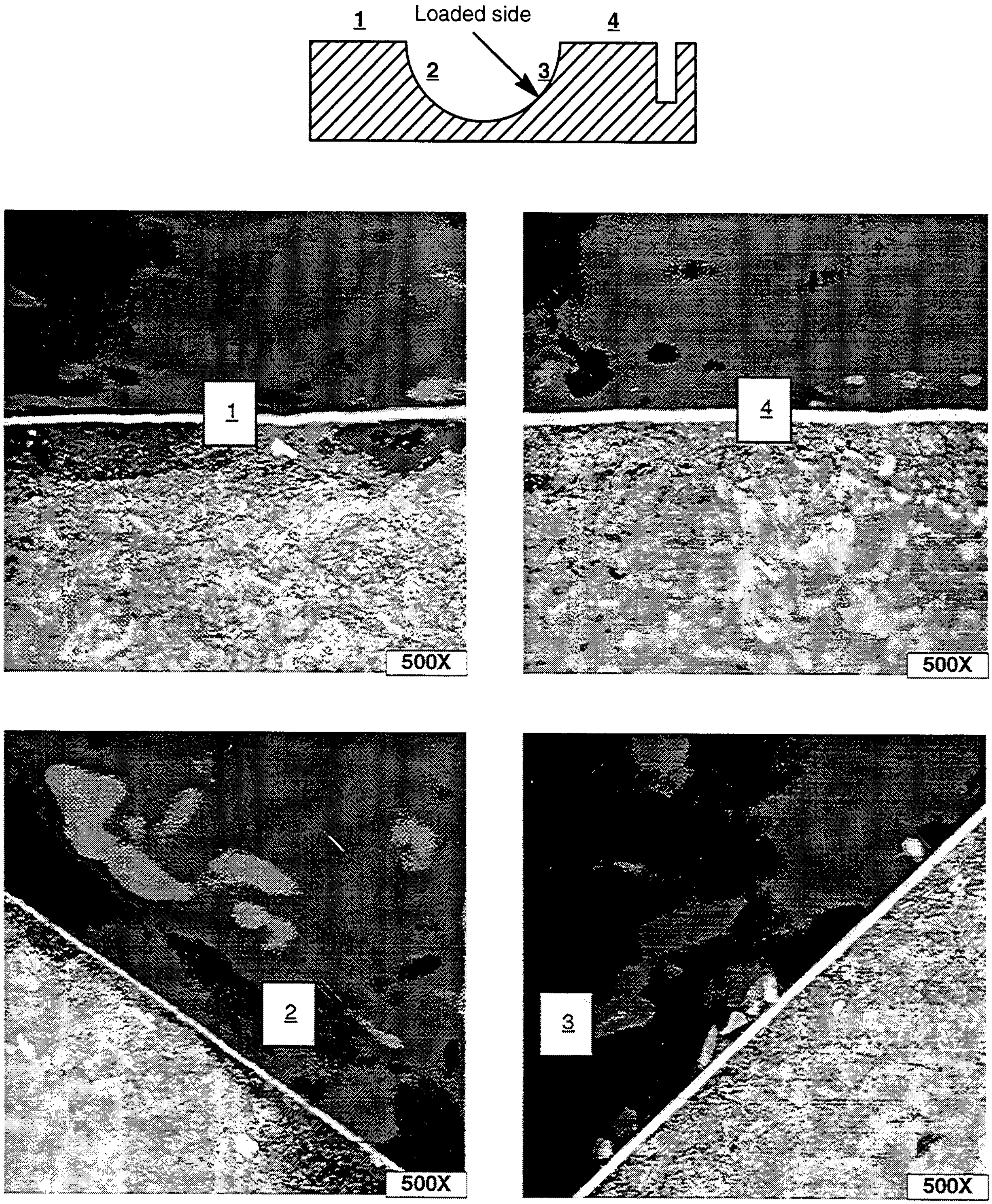


Figure 121. Photos of Off–Oil Tested TDC Bearing S/N MDACE694.
TDC coating demonstrated acceptable off–oil performance.

5.4 Skid Test

FAILED

Skid testing was completed to demonstrate the resistance of TDC coating to damage during skidding and sliding conditions. The TDC coated bearings were considered to successfully complete this testing if the skid damage was equal to or less than that of uncoated bearings. Two TDC coated M50 and two uncoated M50 bearings completed skid testing.

Testing was completed at the following conditions:

- Shaft Speed: 14,900 rpm ±100 rpm
- Thrust Load: 150 lb ±50 lb
- Oil Supply Temperature: 200°F ±5°F

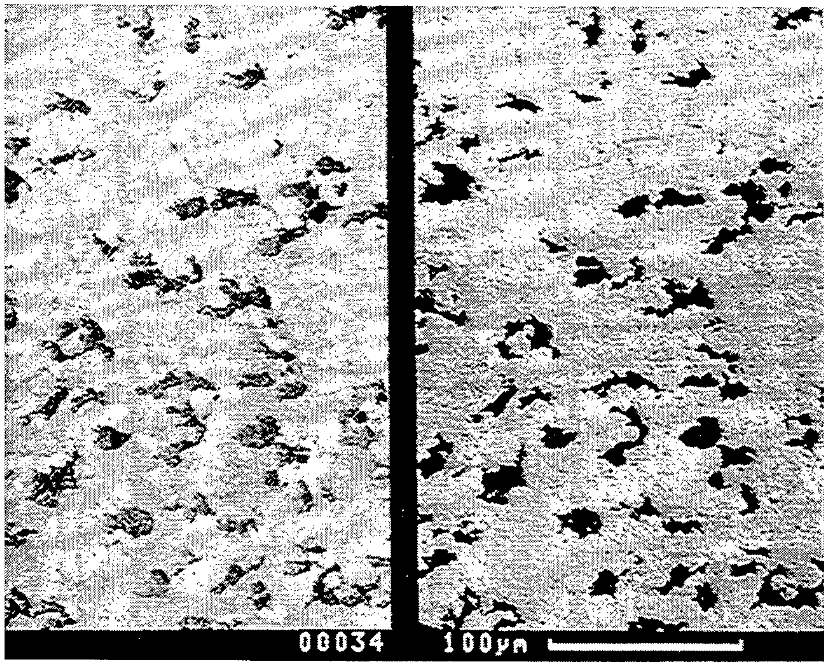
A radial load of 1,000 lb was instantaneously applied to each test bearing while operating at the above conditions. This radial load was applied a minimum of five times in order to create skid conditions.

Results of the skid testing are summarized in **Table** 22. No skid damage was observed on the two uncoated bearings. One of the two TDC coated bearings did experience skid damage.

An area of 0.18 inch wide by 2.25 inch long on the inner race of the TDC bearing had indications of skid damage as TDC was partially removed in this area. In addition, M50 material was transferred from the balls in this skid damage zone. A 250X photograph of the skid damaged raceway is shown in **Figure** 122. The surface of the balls was roughened by the skid damage and the carbides in the M50 material were cracked and smeared as shown in **Figure** 123. Based on these test results, the TDC coated bearings have demonstrated less resistance to damage from skidding conditions.

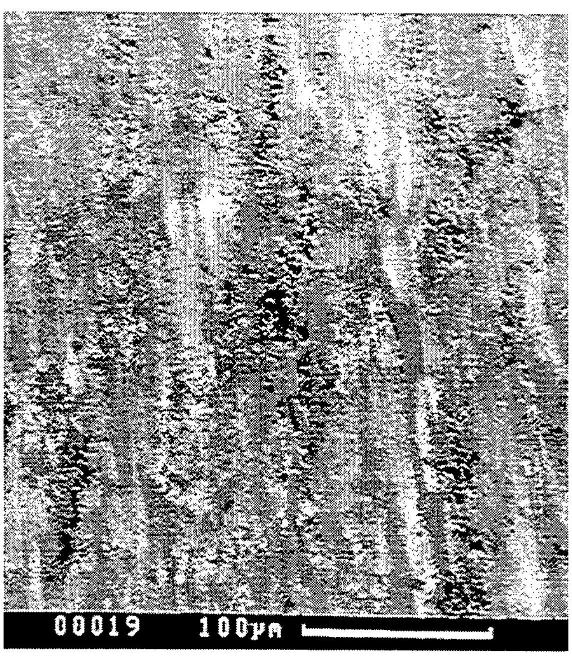
Table 22. Skid Test Results.

SUPPLIER	GE P/N and S/N	RACE/COATING/CAGE PLATE MATERIALS	TEST RESULTS
MRC	9732M10P16 MDA610JV	M50/Silver	No skid damage
MRC	1665M42P01 MDACE701	M50/TDC/Silver	Skid Damage
MRC	9732M10P16 MDA602JV	M50/Silver	No Skid Damage
MRC	1665M42P01 MDACE700	M50/TDC/Silver	No Skid Damage



250X

Figure 122. Microphotograph of Skid Damaged Inner Race TDC on Bearing S/N MDACE700.
Light colored areas in the left image highlight the smeared M50 from the balls. Dark areas in the right image indicate partial TDC pull out.



250X

Figure 123. SEM Photograph of Skid Damaged Ball on Bearing S/N MDACE700.
Carbides (lighter areas) in the right photo appear to be broken up and smaller than undamaged areas of the ball.

5.5 Induced Defect Test

PASSED

Induced defect testing was completed to demonstrate the endurance capability and failure modes associated with continued operation of TDC coated bearings with pretest defects. Successful completion of this testing was based on a comparison of operating times between TDC coated and plain bearings. TDC coated bearings were required to operate for equal to or greater times than plain bearings.

A total of four bearings completed induced defect testing. Two TDC coated and two plain bearings were tested to compare the relative times from spall initiation to cage fracture. A 0.020 inch wide by 0.010 inch deep groove was machined across the entire raceway of each outer ring using an EDM process. **Figure** 124 shows photographs of typical grooves in the raceways prior to test.

Testing was completed at the following conditions:

- Shaft Speed: 13,400 rpm ±100 rpm
- Thrust Load: 7800 lb ±50 lb
- Oil Supply Temperature: 210°F ±10°F

Testing continued at these conditions for 100 hours or until complete fracture of the bearing cage.

Table 23 summarizes the results of this induced defect testing. As noted, the TDC M50 bearing operated for a longer period than the equivalent uncoated M50 bearing. The TDC coated and uncoated M50NiL bearings operated for basically an equivalent time period.

Figures 125 and 126 illustrate the raceway conditions of each bearing after testing. Comparing the postdefect operational damage of the plain bearings (**Figure** 125) with the TDC coated bearings (**Figure** 126) indicates less damage on the TDC coated bearings.

These test results demonstrate the successful operational life and characteristics of TDC coated bearings with induced defects.

5.6 Thermal Cycle Test

PASSED

Thermal cycle testing was completed to demonstrate the capability of TDC coatings to withstand minimum and maximum engine operating temperatures. Test results were considered successful if there was no evidence of TDC coating cracking or separation from the base bearing material.

Three complete TDC coated bearings finished thermal cycle testing. Two bearings included M50 races and the third bearing included M50NiL races.

Thermal cycle testing consisted of exposing all bearings to 100 temperature cycles from –65°F to 600°F. All bearings were held at each extreme temperature for 45 minutes during each cycle.

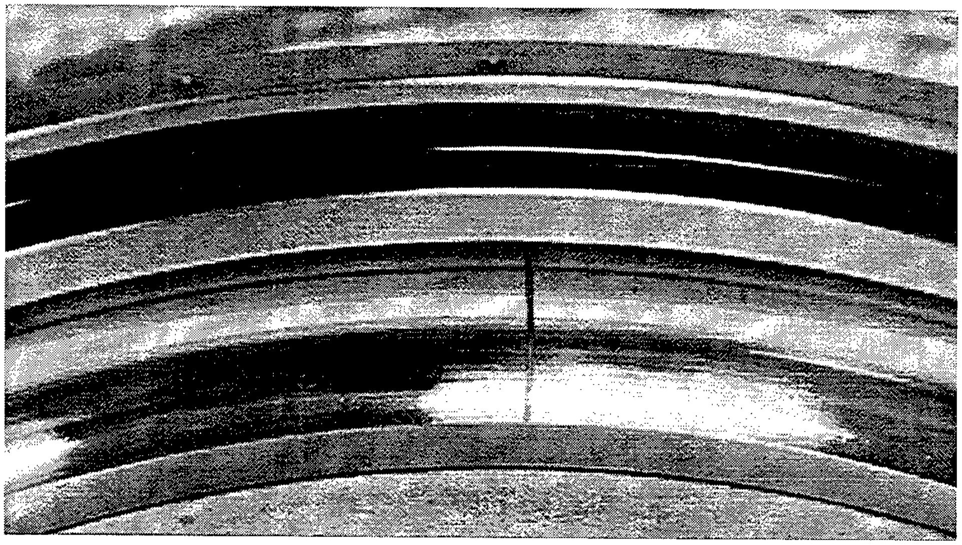
Table 24 summarizes the successful test results. Posttest inspection results indicated no evidence of TDC cracking and no evidence of TDC coating separation from the base bearing material.

5.7 Corrosion Resistance Demonstration Test

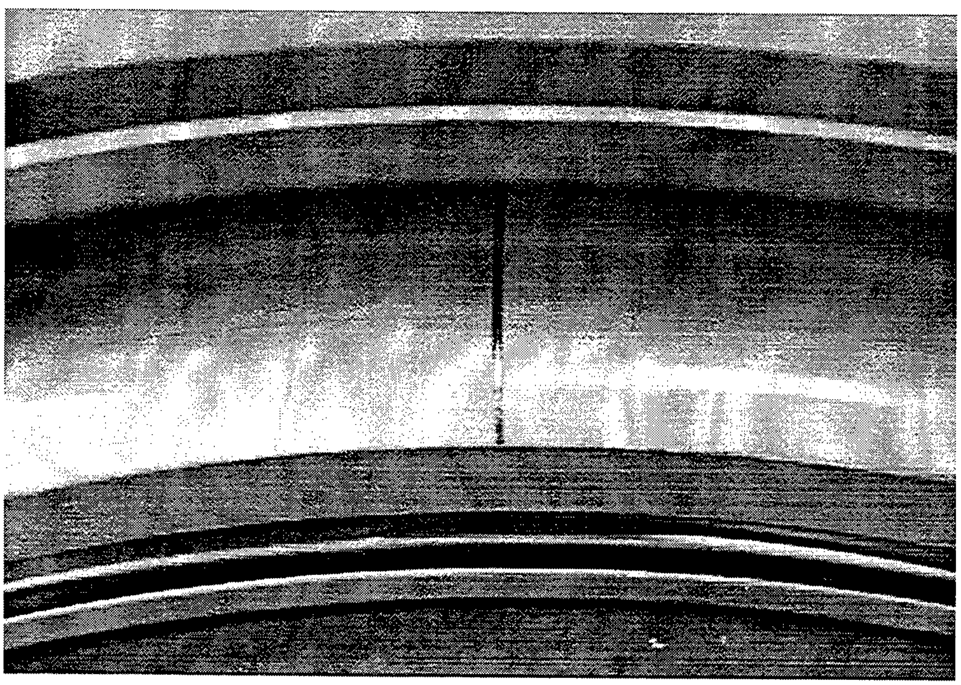
PASSED

Testing was completed to compare the relative corrosion resistance of TDC coated versus plain bearings.

The outer races of four TDC coated bearings and two plain bearings were exposed to normal atmospheric conditions for 450 hours. All bearing races were simultaneously hung in an outside test area with partially open front and sides, exposing the test parts to normal atmospheric conditions.



EDM Groove in Plain Outer Race
P/N 9732M10P16
S/N MDA605JV



EDM Groove in TDC Coated Outer Race
P/N 1665M42P01
S/N MDACE693

Figure 124. Photos of EDM Groove Machined in Outer Race for Induced Defect Test.

Table 23. Induced Defect Test Results.

SUPPLIER	GE PART NUMBER	RACE/COATING/ CAGE PLATE MATERIALS	HOURS TO FIRST CHIP	TEST TIME (HRS.)
MRC	9732M10P16 MDA605JV	M50/SILVER	15.3	78.1
MRC	1665M42P01 MDACE693	M50/TDC/SILVER	2.0	100 HRS. SUSPENDED
SBB	1461M15P06 MABS1879	M50NiL/TiN/SILVER	5.1	55.7
SBB	1665M45P01 MABS6757	M50NiL/TDC/SILVER	2.6	50.2

As noted in the test results summarized in **Table** 25, the plain bearings experienced extensive corrosion. Three of the four TDC coated bearings had no evidence of corrosion. A fourth TDC coated bearing had four corrosion pits on the bearing face. These corrosion pits were initiated by cracks and/or pin holes in the TDC coating which exposed the base M50 material to the atmosphere.

Figures 127 and 128 illustrate the conditions of the test races after atmospheric exposure. As evidenced by these photographs, the TDC coating provides a significant increase in corrosion resistance compared to plain bearings.

Figure 125. Photos of Plain Bearing Race Damage Evident after Induced Defect Test.

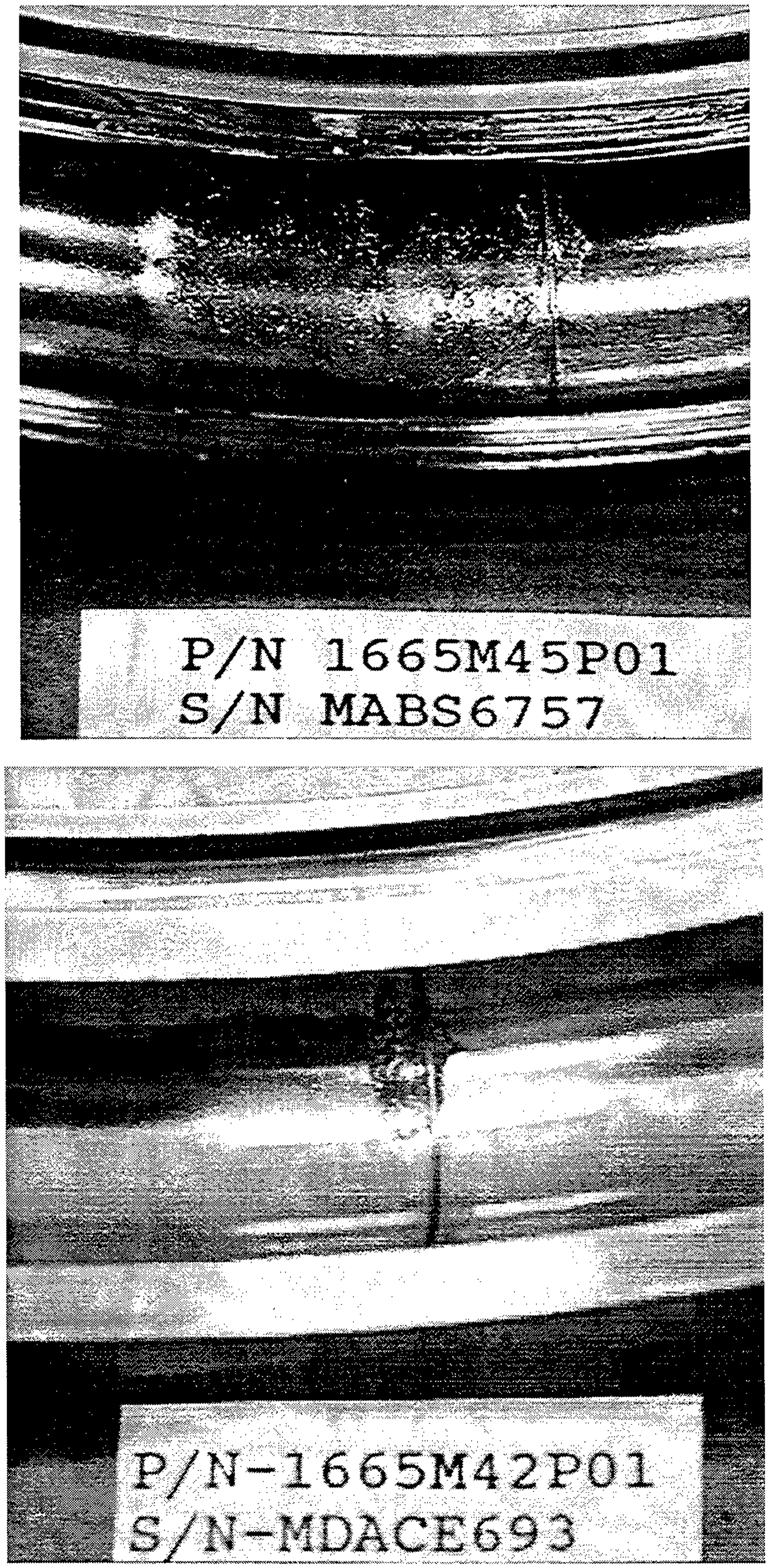


Figure 126. Photos of TDC Coated Bearing Race Damage Evident after Induced Defect Test.
Note reduced level of damage compared to plain bearings Figure 125.

Table 24. Thermal Cycle Test Results.

SUPPLIER	GE P/N and S/N	RACE/COATING/CAGE PLATE MATERIALS	TEST RESULTS
MRC	1665M42P01 MDACE697	M50/TDC/Silver	Successful
SBB	1665M45P01 MABS9638	M50Nil/TDC/Silver	Successful
SBB	1665M46P01 MABR9919	M50/TDC/Silver	Successful

Table 25. Corrosion Resistance Test Results.

OUTER RACE SERIAL NUMBER	RACE MATERIAL/ COATING	PART HISTORY	TEST RESULTS
SNR00173	M50	New Part	Extensive Corrosion
MDA605JV	M50	Induced Defect Tested	Extensive Corrosion
MDACE697	M50/TDC	Thermal Cycle Tested	4 Corrosion Pits on Face
MABS9632	M50/TDC	Op. Endurance Tested	No Corrosion
MABS6867	M50NiL/TDC	Op. Endurance Tested	No Corrosion
X097	M50NiL/TDC	New Part	No Corrosion

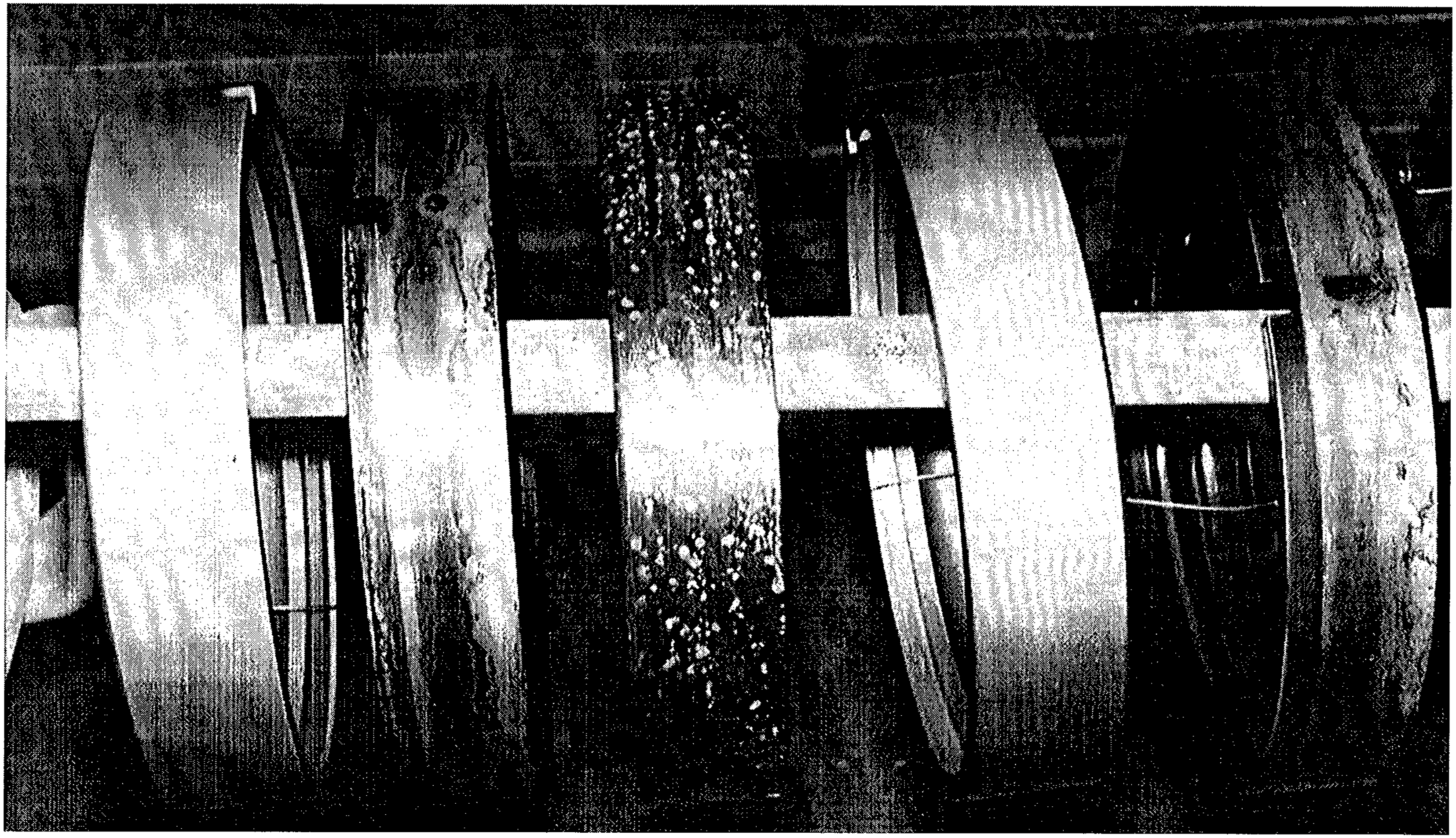
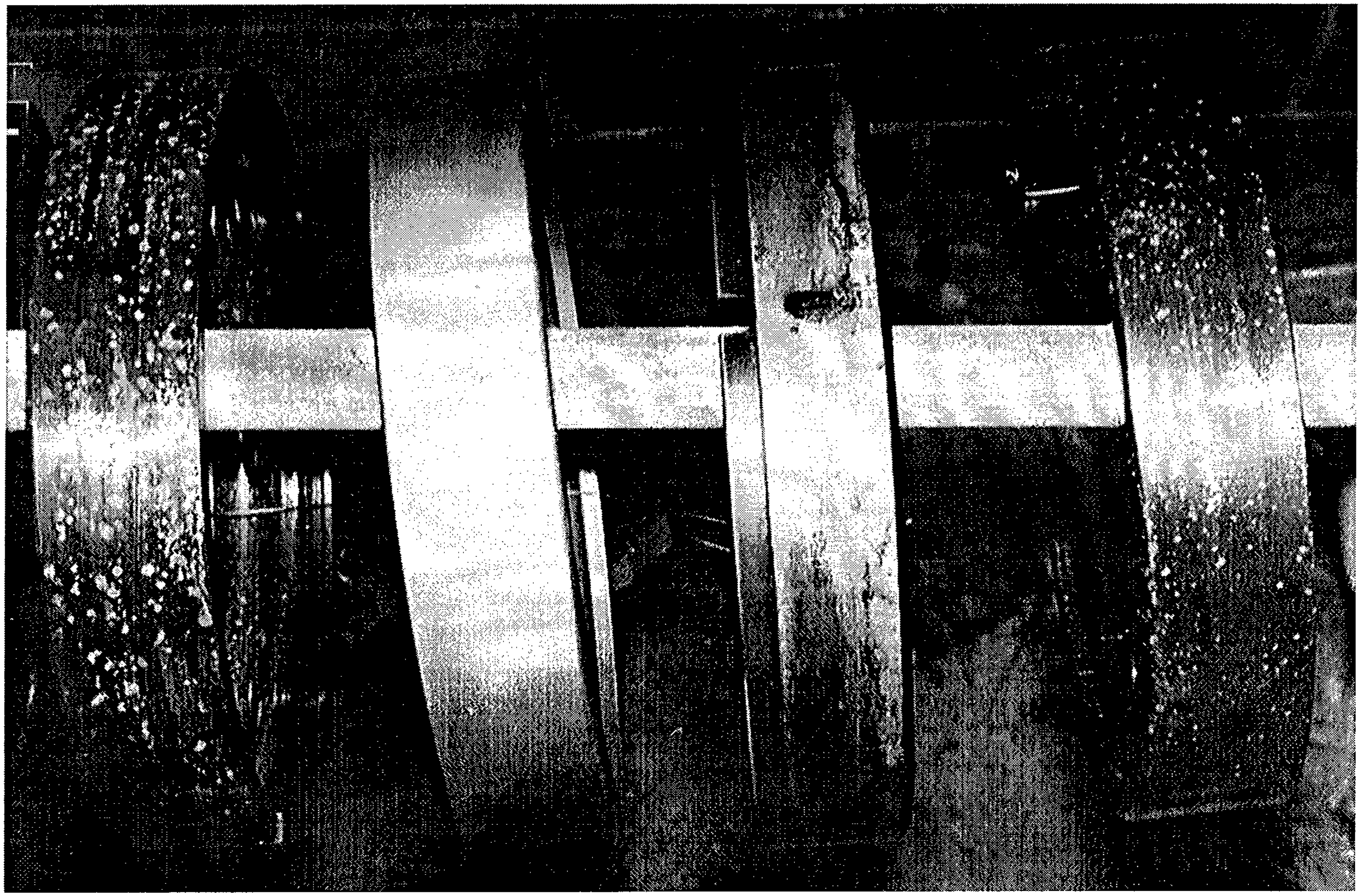


Figure 127. Photos of Corrosion Resistance Test Bearings.
TDC coating significantly improved corrosion resistance.



New Plain Bearing | New TDC Coated Bearing | Endurance Tested TDC Coated Bearing | New Plain Bearing

Figure 128. Photos of Corrosion Resistance Test Bearings.
TDC coating significantly improved corrosion resistance.

6.0 Engine Assembly Evaluation

F110 No. 4R roller bearings were used to complete a series of bearing installations and removals on engines. The No. 4R roller bearings included TDC coated rollers and races. The objective of this test was to evaluate the tolerance of TDC coated bearings to potential engine assembly and disassembly damage.

A total of four bearings were installed and removed from F110–GE–100 and –129 engines. Three of the four bearings experienced unacceptable damage from this test as follows:

- Numerous axial scratches in the outer race caused by the TDC rollers sliding across the TDC raceway during assembly and disassembly.
- TDC removed from both rollers and races in the areas where the rollers slid across the race.
- TDC and M50 material transferred from races and smeared onto rollers.

Figures 129, 130 and 131 are photographs of these conditions. Figure 131 is a SEM photograph of a typical roller in the area where TDC and M50 material was transferred from the race.

Based on these results, it is concluded that the sliding or shear forces during installation or removal of the No. 4R roller bearing were greater than the adhesive strength of the TDC coating to the base material.

TDC coating of the No. 4R bearing was not recommended due to the increased susceptibility to assembly damage.

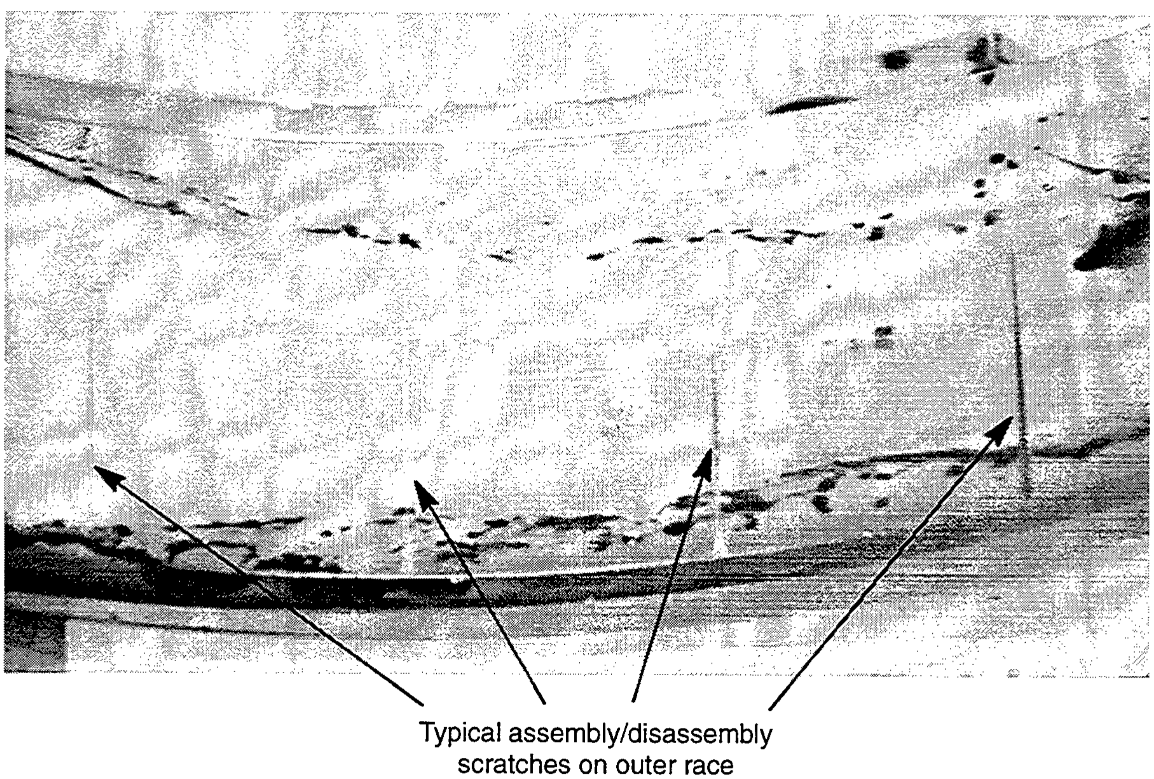


Figure 129. Photo of F110 No. 4R Bearing Outer Race TDC Coating Assembly Damage.

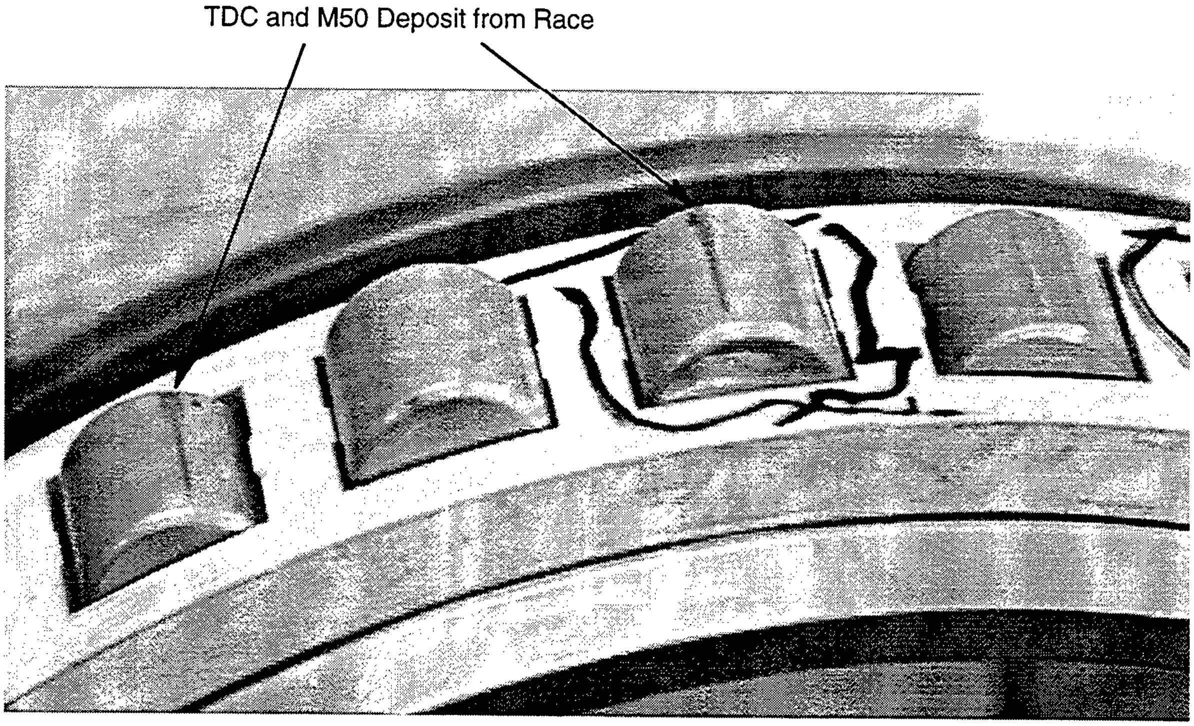


Figure 130. Photo of Assembly Damage to Roller TDC Coating.

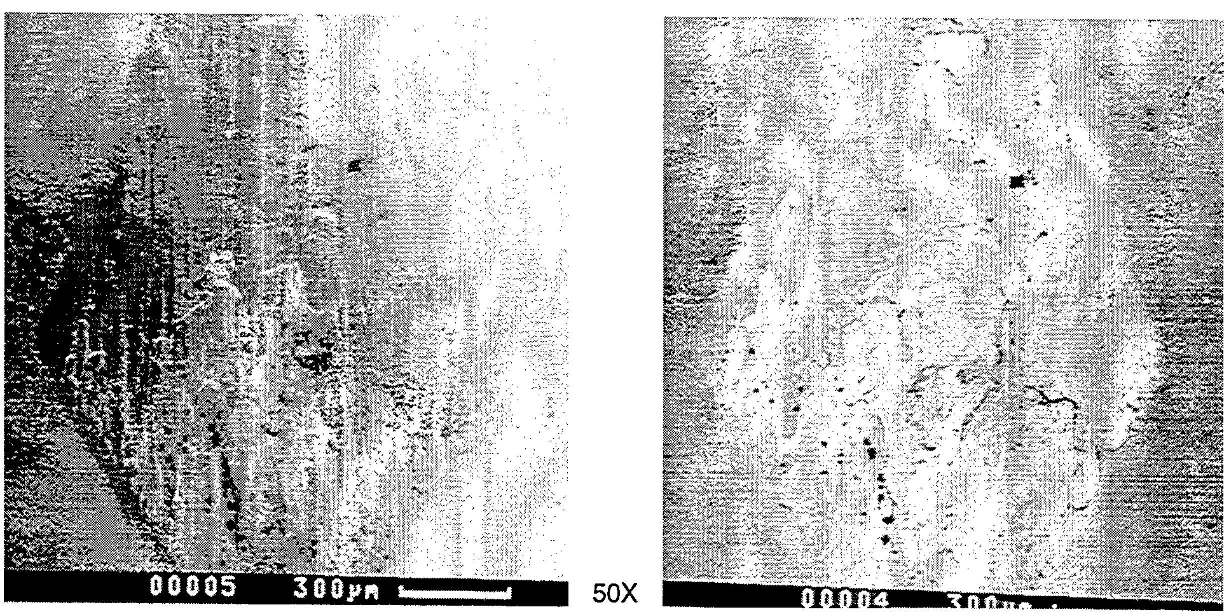


Figure 131. SEM Secondary and Backscatter Photos of Roller Assembly Damage.
Smeared areas indicate M50 material deposited from the race.

7.0 Engine Accelerated Mission Cycle Testing

Two F110 engines completed accelerated mission cycle testing with TDC coated bearings at all engine mainshaft positions. TDC coated rollers and races were included in the three mainshaft roller bearings (No. 1R, 4R, and 5R positions). The objective of this testing was to demonstrate the endurance capability of TDC coated bearings in actual engine environments.

7.1 F110–GE–129 Engine Serial No. 538–103/4 Test Results

FAILED

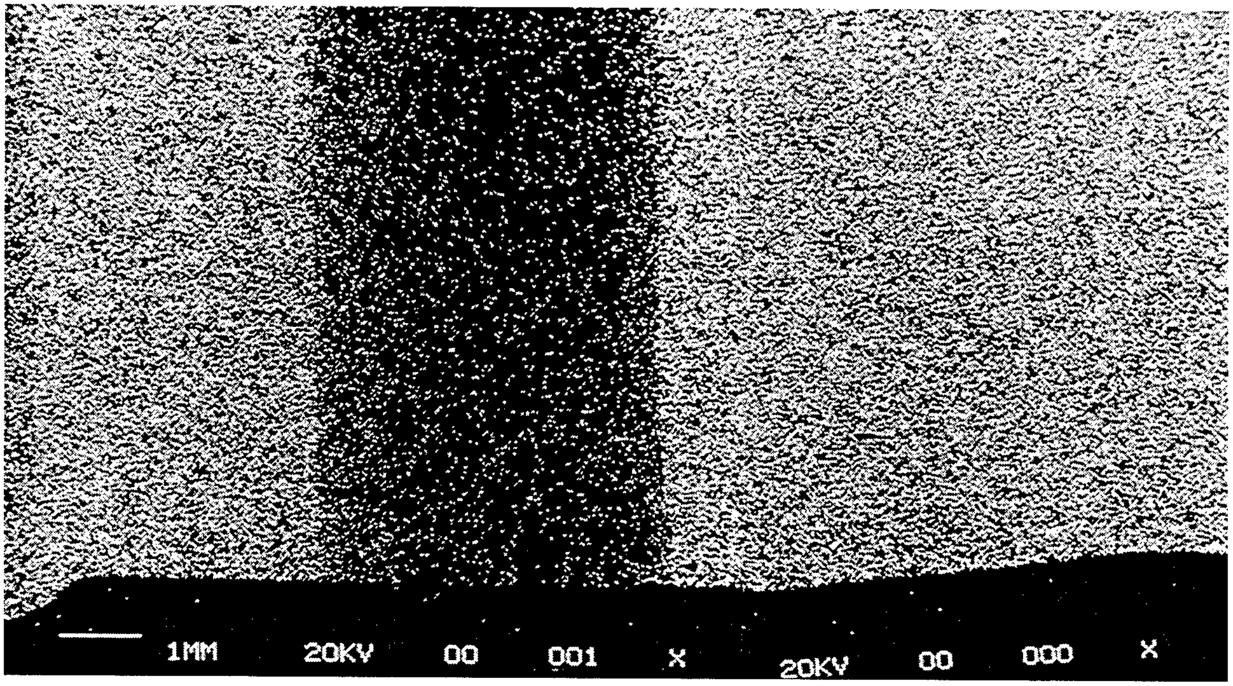
Table 26 summarizes the accumulated test results for the TDC bearings on F110–GE–129 ESN 538–103/4. Bearing inspection results indicated that the No. 1R, 2B, and 4R bearings were in acceptable condition based on in–service engine inspection criteria. The No. 3B and 5R bearing conditions were not acceptable.

The No. 3B bearing experienced skid damage which resulted in removal of the TDC in the skid affected area of the race and spalling of one ball. **Figure** 132 is an energy dispersive spectroscopy dot map of the raceway ball track looking for chromium. TDC had been removed as indicted by the dark band in this photograph. **Figure** 133 is a SEM photograph of the spalled ball. Spalling originated at the surface, probably as a result of the skidding action which damaged the TDC coated race.

Routine inspection of the No. 5R bearing after only 7 hours of testing indicated numerous areas of partial peeling of the TDC coating on the inner race. **Figure** 134(a) is a SEM photograph of a typical area of partial TDC coat peeling. Evidence of TDC is still present in these areas indicating that the peeling occurred between the first and second layer of TDC. **Figure** 134(b) is a SEM photograph of an area adjacent to partial peeling. The adjacent coating has been polished by the TDC which was liberated in the partially peeled areas. Although peeling of the TDC coating is an unacceptable condition, it was decided to continue testing this bearing to evaluate damage tolerance and endurance. Final posttest inspections did not indicate any measurable changes in the TDC peeling conditions.

Table 26. F110–GE–129 ESN 538–103/4 Test Results Summary.

Bearing	Total Test Time	Inspection Results
#1R	813 Hours	Acceptable
#2B	813 Hours	Acceptable
#3B	813 Hours	Not Acceptable; Skid Damage; Ball Spall; TDC Removed in Skid Areas of Race
#4R	281 Hours	Acceptable
#5R	281 Hours	Not Acceptable; Partial Peeling of TDC on Inner Race



10X

Figure 132. Energy Dispersive Spectroscopy of F110–GE–129 ESN 538–103/4 No. 3 Bearing.
Dark band in the center of the dot map indicated the TDC has peeled away. TDC coating is susceptible to operational skid damage.

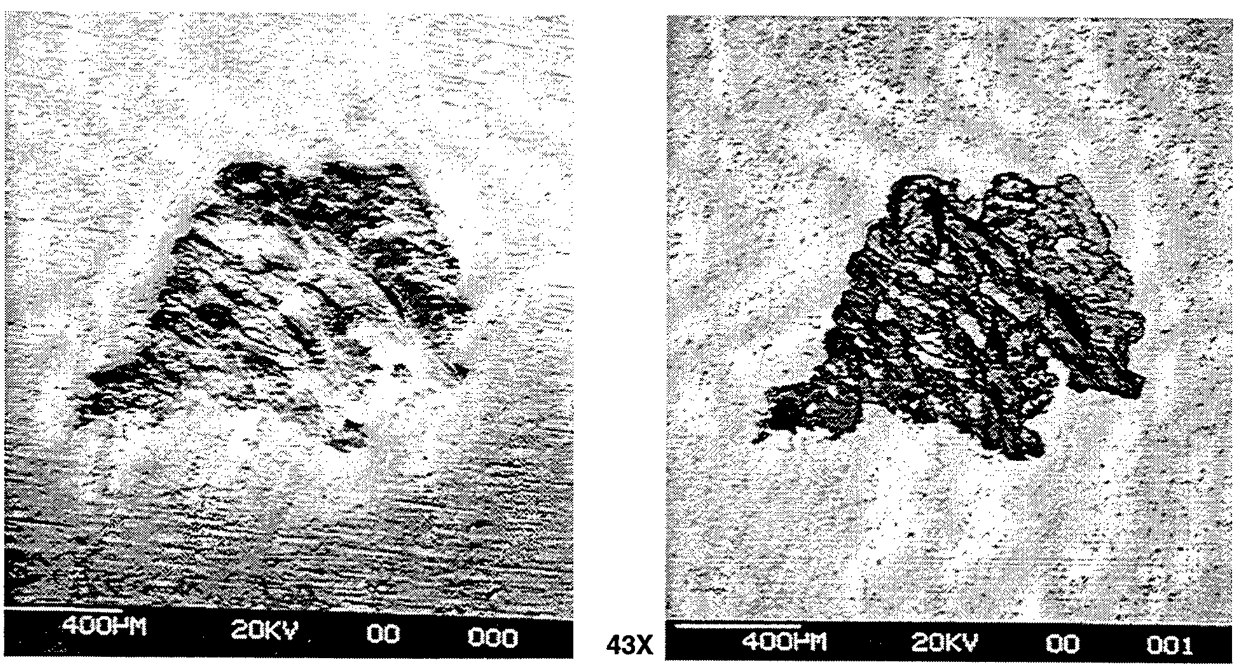
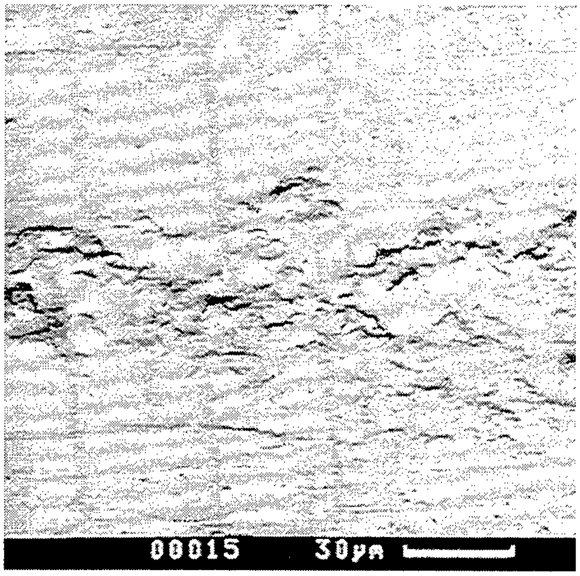
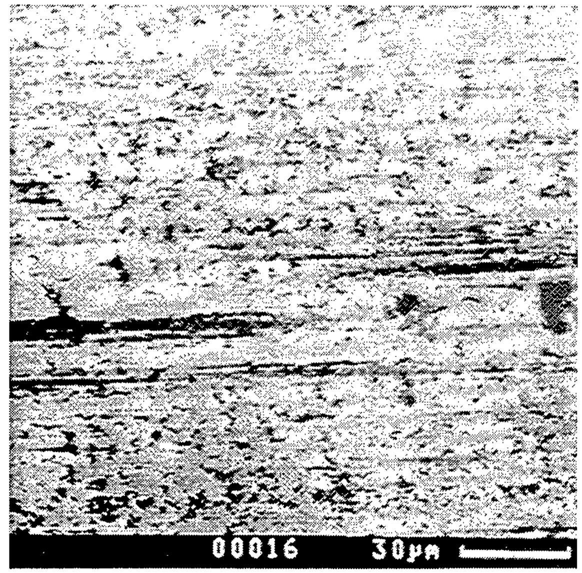


Figure 133. SEM Secondary and Backscatter Photos of Ball Spall.
Skid damaged TDC coating initiated ball spalling in test of ESN 538–103/4 bearing.



(a) Peeled TDC



(b) Polished TDC

Figure 134. SEM Backscatter Photos of No. 5 Bearing Inner Race Damage.
TDC coating is susceptible to peeling as evidenced in test of ESN 538–103/4 bearing.

7.2 F110–GE–100 Engine Serial No. 509–716/5 Test Results

FAILED

Table 27 summarizes the accumulated engine test results for the TDC bearings on F110–GE–100 ESN 509–716/5. Bearing inspection indicated that the No. 3B and 5R bearings were in acceptable condition based on in–service engine inspection criteria. The No. 2B bearing condition was marginally acceptable and the No. 1R and 4R bearing conditions were not acceptable.

Table 27. F110–GE–100 ESN 509–716/5 Test Results Summary.

Bearing	Total Test Time	Inspection Results
#1R	449 Hours	Not acceptable; assembly damage deep scratches, TDC peeling
#2B	700 Hours	Marginal; micro-peeling due to skid damage
#3B	700 Hours	Acceptable
#4R	555 Hours	Not acceptable; bearing failure; large spalled area
#5R	555 Hours	Acceptable

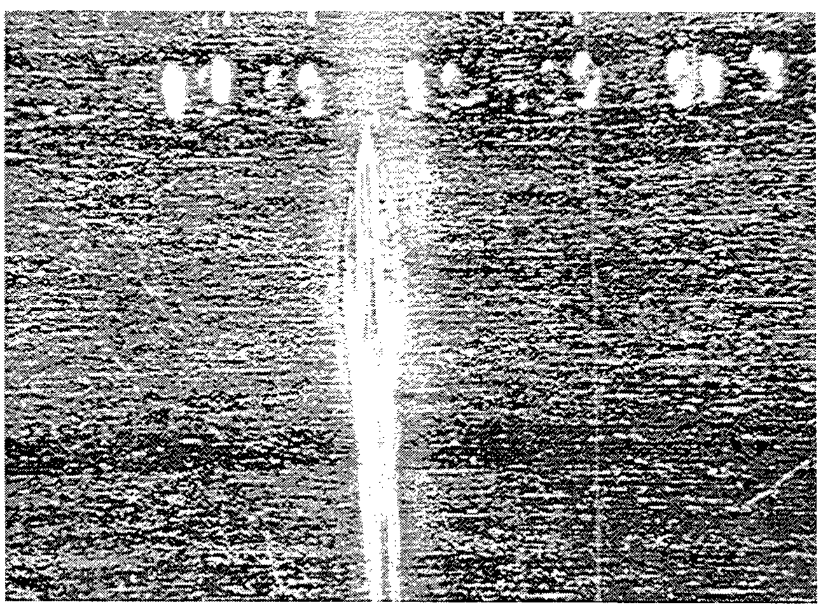
Routine inspection of the No. 1R bearing after 449 hours of engine testing indicated several deep axial scratches on the inner race. In addition, the inner race had a circumferential ring of dents which are aligned with the edge of the scratches and localized partial TDC peeling adjacent to some dents.

The axial scratches breech the TDC coating and extend into the base M50 material. These scratches were caused by damage during engine assembly when the TDC coated rollers axially slide against the TDC coated race. The circumferential ring of dents was probably caused by raised material on the rollers (transferred from race). Localized TDC peeling was considered secondary damage due to continued operational forces at the edges of the dents. **Figure** 135 is a photograph of a typical axial scratch and the adjacent dents.

An unscheduled engine teardown was completed after 555 hours total run time due to M50 chips collecting on the engine chip detector. Inspection results indicated a large spalled area (0.5 inch wide × 3.5 inches long) on the No. 4R bearing outer race. In addition, several axial scratches and dents were found on the outer race and lead–in chamfer. **Figure** 136 is a photograph of the spalled outer race which is still installed in the bearing housing. The axial scratches were caused by assembly damage which in turn initiated the spalling. Assembly damage is suspected to have occurred following a low pressure turbine disassembly inspection 70 hours prior to the bearing failure.

The posttest condition of the No. 2B bearing was considered marginal. Although the condition of the bearing was within inspection limits, there was evidence of undesirable skid damage on the inner race. A circumferential ring of partially peeled TDC areas was present in the location where skidding is likely to occur. **Figures** 137, 138 and 139 are SEM photographs of these areas. **Figure** 139 highlights a typical area adjacent to a location of partially peeled TDC. Secondary polishing and micro–peeling of the TDC has occurred in these areas.

Similar to previous rig and engine test results, these test results indicate the TDC coated bearings are susceptible to roller bearing assembly damage and ball bearing skid damage.



20X

Figure 135. Photo of F110–GE–100 ESN 509–716/5 No. 1R Bearing Inner Race Scratch/Dents.
TDC coating roller bearings demonstrated reduced assembly damage resistance.

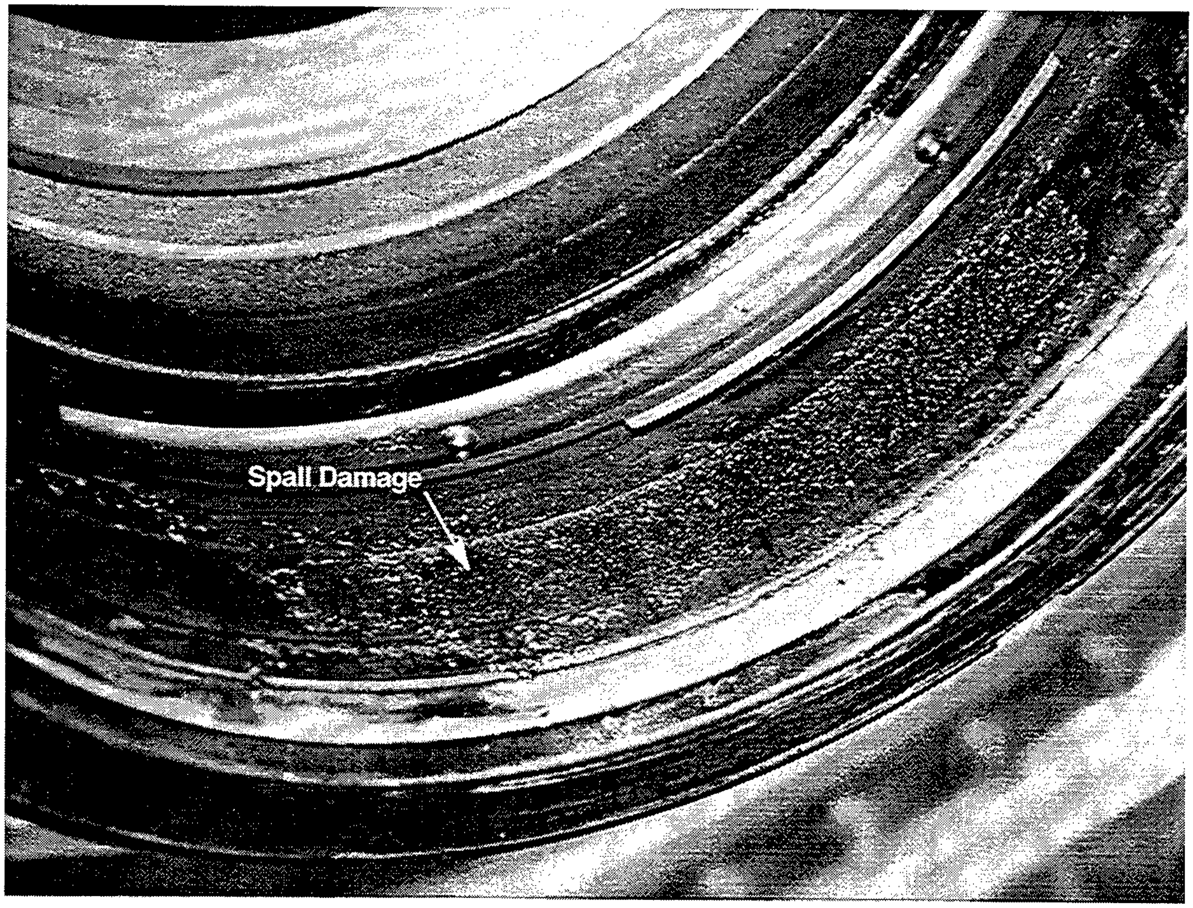
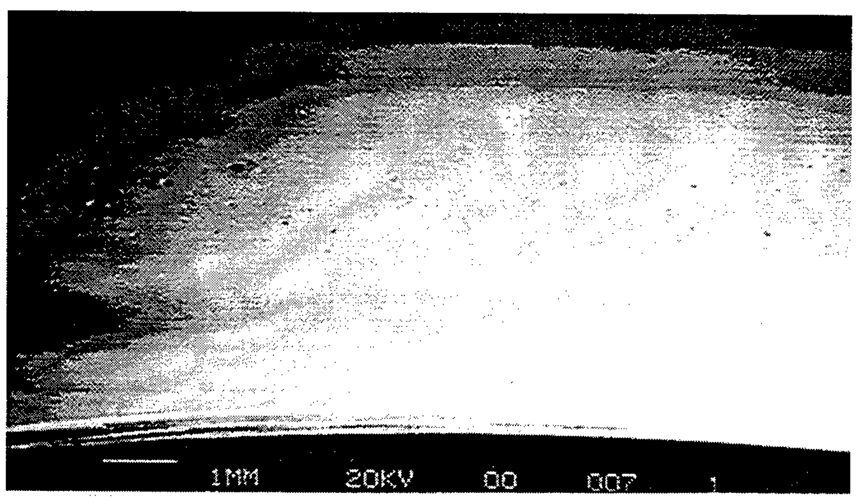


Figure 136. Photo of F110–GE–100 ESN 509–716/5 No. 4R Bearing Outer Race Spall.

Edge



10X

Figure 137. SEM Photo of F110–GE–100 ESN 509–716/5 No. 2B Bearing Inner Race.
Note band of dimples indicating micropeeling.

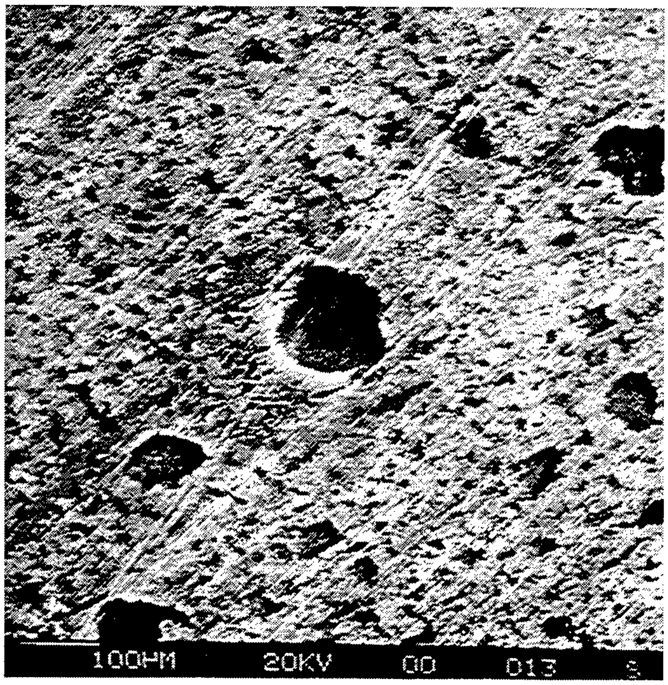


Figure 138. SEM Secondary Photo of F110–GE–100 ESN 509–716/5 No. 2B Bearing Inner Race.

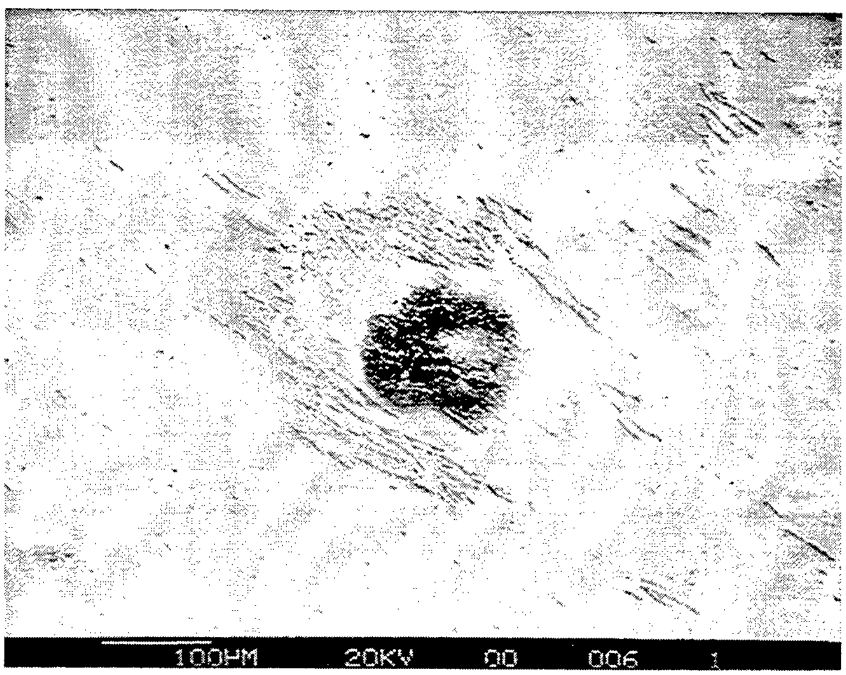


Figure 139. SEM Backscatter Photo of F110–GE–100 ESN 509–716/5 No. 1R Bearing Inner Race. *TDC micropeeling results in secondary damage.*

8.0 Conclusions

The program objective to thoroughly evaluate the benefits and risks associated with inserting TDC coated bearings into in–service F101 and F110 engines was successfully achieved as documented in this report.

The benefits of TDC coated mainshaft bearings were clearly demonstrated by the significant increase in resistance to contamination and corrosion compared to plain bearings. TDC coating performance also proved to be acceptable during oil–off and induced defect operating conditions.

However, TDC coating performance was not acceptable relative to consistent quality characteristics, rolling contact fatigue life at low–Lambda conditions, skid damage tolerance, engine assembly damage resistance, and engine operational endurance capabilities.

The nodular TDC coating experienced failures in the areas of thickness, topography, salt spray corrosion, hydrogen embrittlement, and rolling contact fatigue throughout the vendor qualification program. None of the MRC or SBB subscale Round 1 or 2 testing series were able to completely satisfy all of the qualification requirements.

It is important to recognize that the effect of the TDC topography on Lambda is a common concern to both the MRC and SBB subscale fatigue tests, and is consistent with the point surface originated failures, the larger amount of white etching layer, and the visible ball tracks of the TDC coated bearings. Although nodular TDC has performed well in the past, these were generally under conditions of high Lambda or in contaminated conditions. The effects of the nodularity of the TDC appear to be negative in a clean, low Lambda environment when compared to bearings which typically have fine surface finishes.

It is believed that the Lambda (or some other inherent property) of the nodular TDC coating resulted in an acceleration of material degradation, particularly at high contact stresses. Even if TDC can be deposited in a manner in which it is esentailly smooth, concerns still exist with regard to the coatings ability to remain adherent to the bearing surface in situations which would involve low Lambda and high sliding or skidding forces.

These risks and shortcomings associated with TDC coated bearings are greater than the benefits. Therefore, TDC coated bearings are not recommended for insertion into F101 and F110 engines.

9.0 Recommendations

9.1 Recommendations Based Upon MRC Subscale Testing (Sections 4.2.1 and 4.2.2)

Since neither Round No. 1 nor No. 2 were able to pass all of the qualification tests, nodular TDC would not be recommended at this time.

Issues existed with the RCF results in the first round of MRC testing; cracking of the TDC, corrosion failure, hydrogen embrittlement failure in the second round of testing, and an accelerated subsurface microstructural distress in both Rounds 1 and 2.

9.2 Recommendations Based Upon SBB Subscale Testing (Sections 4.2.3 and 4.2.4)

Since neither Round No. 1 or No. 2 were able to pass all of the qualification tests, TDC could not be recommended.

Issues exist with the RCF results in the first round of SBB testing; thickness of the TDC , corrosion failure, and RCF test failures in the second round of testing.

9.3 Recommendations Based Upon Overall Subscale Testing

Based on the results of the subscale testing, NTDC would not be recommended in applications which are relatively clean and subject to low Lambda conditions.

9.4 Overall Recommendations

Although the concept of using plating for corrosion protection is viable in many applications, it is not the best long term solution for aircraft engine mainshaft bearings. It is recommended that other options be considered and pursued to provide increased corrosion protection. High chrome steel material development and qualification is one recommended approach.

These risks and shortcomings associated with TDC coated bearings are greater than the benefits. Therefore, TDC coated bearings are not recommended for insertion into F101 and F110 engines.

Appendices

Appendix A MRC Round No. 1 Supplemental Data

ARMOLOY®

CERTIFICATION NO.
Nº C- 7003

— CERTIFICATION —

PRECISION HARD DENSE CHROMIUM FOR WEAR AND CORROSION PROTECTION IN INDUSTRY

TO: MRC BEARINGS
FALCONER PLANT
MAROCO ROAD
FALCONER NY 14733

ORDER NO.:

DATE: 06/02/93

NTITY	DESCRIPTION	ARMOLOY PROCESS SPECIFICATION
1	3095 INNER RINGS	PER ES-285 AND GE F50TF91 PER ES-285 PARA. 13 A-K A) NO PO# B) 3095 OUTER SERIAL NUMBERS ON RECORD C) ES-285 02/23/93 D) 25 E) 06/17/93 F) 37693 G) ATTACHED H) ADHESTION TEST RESULTS ACCEPTABLE I) ACCEPTABLE J) PARTS WERE PROCESSED IN ACCORDANCE WITH PROCESS PARAMETERS ESTABLISHED IN PROCESS SPECIFICATION #37693-B K) ALL THICKNESS MEASUREMENTS & TEST RESULTS MEET MRC ES-285 AND GE F50TF91 REQUIREMENTS

ies that these parts were Armoloy Processed with Certified Armoloy Materials in accordance with guidelines set forth by
of Connecticut, Inc., and will meet or exceed specification requirements for this order. Q. C. INSPECTOR

AUTHORIZED BY: Charles Glover

Figure A–1. Certification of Armoloy TDC Plating for Inner Rings.

ARMOLOY®

CERTIFICATION NO.
Nº C- 7039

— CERTIFICATION —

PRECISION HARD DENSE CHROMIUM FOR WEAR AND CORROSION PROTECTION IN INDUSTRY

TO: MRC BEARINGS
FALCONER PLANT
MAROCO ROAD
FALCONER NY 14733

ORDER NO.:

DATE: 06/02/93

ITY	DESCRIPTION	ARMOLOY PROCESS SPECIFICATION
	309S OUTER RINGS	PER ES-285 AND GE F50TF91 PER ES-285 PARA. 13 A-K A) NO PO# B) 309S OUTER SERIAL NUMBERS ON RECORD C) ES-285 02/23/93 D) 25 E) 06/30/93 F) 37693 G) ATTACHED H) ADHESTION TEST RESULTS ACCEPTABLE I) ACCEPTABLE J) PARTS WERE PROCESSED IN ACCORDANCE WITH PROCESS PARAMETERS ESTABLISHED IN PROCESS SPECIFICATION #37693-B K) ALL THICKNESS MEASUREMENTS & TEST RESULTS MEET MRC ES-285 AND GE F50TF91 REQUIREMENTS

. that these parts were Armoloy Processed with Certified Armoloy Materials in accordance with guidelines set forth by Connecticut, Inc., and will meet or exceed specification requirements for this order. Q.C. INSPECTOR

AUTHORIZED BY: Charles Glover

Figure A–2. Certification of Armoloy TDC Plating for Outer Rings.

Westmoreland Mechanical Testing & Research Inc.
Specialists in the Aviation and Nuclear Fields

Old Route 30, Westmoreland Drive
P.O. Box 388, Youngstown, Pa. 15696-0388 U.S.A.
Telephone: 412 537-3131 Fax: 412 537-3151

2 February 1994
Corrected Date: 15 August 1994

MRC Bearings
402 Chandler Street
Jamestown, NY 14701-3802

WMT&R Report: 4-00585
P.O. No.: 0202023079
Shipping No.: 113778

Attention: Mr. Louis J. DiMassa, Jr.

Subject: Salt Spray Corrosion Testing Per ASTM B-117 and AMS S-2438

Introduction:

One (1) 309 size inner ring GE TDC 39, identified as sample no. 21, was receive in the laboratory and exposed for 24 hours to the salt fog test of ASTM B117 an AMS 2438, with the following results.

Results:

After the 24 hour exposure, the ring was gently washed in cool, clean water, and dried per specification requirements. Examination showed the flat face marked as GE TDC 39 to contain the most rust spots. The ring rested on the opposite face marked Test 1 at a slight angle in the chamber on a coated rack. Other rust spots were observed on the OD, ID, and top surfaces. Although the rust appears to be generated at some pits, the worst areas seem to come near stamp marks, vibrated marks edges and corners on the sample.

If you have any further questions, please feel free to contact me.

At your service

Andrew M. Wisniewski
Plant Manager

tmr

KNOWINGLY OR WILLFULLY FALSIFYING OR CONCEALING A MATERIAL FACT ON THIS FORM, OR MAKING FALSE, FICTITIOUS OR FRAUDULENT STATEMENTS OR REPRESENTATIONS HEREIN COULD CONSTITUTE A FELONY PUNISHABLE UNDER FEDERAL STATUTES.

Figure A–3. Corrosion Test Results from Westmoreland Mechanical Testing & Research, Inc.

Westmoreland Mechanical Testing & Research Inc.
Specialists in the Aviation and Nuclear Fields

P.O. Box 388, Youngstown, Pa. 15696-0388 U.S.A.
Telephone: 412-537-3131 *Fax: 412-537-3151*

MRC Bearings
SKF Aerospace Bearings
402 Chandler Street
Jamestown, NY 14701

ATTN: Mr. Ray Jones

DATE: 9/8/93
P.O. No.: 0202023079
Shipping Auth.: 109895
Req. No.: 55164
WMTR REPORT NO.: 3-07160

SHEET 2 of 2

SHARP NOTCH TENSION CERTIFICATION

MATERIAL Submitted As	M50	M50	M50		
HEAT Number	———	———	———		
SAMPLE Number	1	3	4		
Orientation	———	———	———		
Temperature, °F	Room	Room	Room		
Test Section Length L, in.	———	———	———		
Major Diameter D, in.	.3337	.3334	.3333		
Notch Diameter d, in.	.2340	.2350	.2351		
Notch Area, sq. in.	.04300526	.04337362	.04341054		
Notch Root Radius, in.	.010	.010	.010		
PMAX P, lbs.	9841	11790	8495		
Sharp Notch Strength, ksi	228.8	271.8	195.7		
Yield Strength, ksi	———	———	———		
Notch Yield Ratio	———	———	———		
Minimum Acceptable Ratio	———	———	———		
Pass/Fail	———	———	———		
Machine No.	M7	M7	M7		
Test Log No.	049039	049040	049041		

KNOWINGLY OR WILLFULLY FALSIFYING OR CONCEALING A MATERIAL FACT ON THIS FORM, OR MAKING FALSE, FICTITIOUS OR FRAUDULENT STATEMENTS OR REPRESENTATIONS HEREIN COULD CONSTITUTE A FELONY PUNISHABLE UNDER FEDERAL STATUTES.

SRL
T-003-01

SPECIFICATION (LABORATORY COMMENTS): All testing done at WMT&R, Inc.
Average UTS = 232,115 PSI
ASTM E602

CERTIFIED BY: Robert J. Sitko
Robert J. Sitko
Tech Service Manager

9/8/93
September 8, 1993

Figure A–4. Sharp Notch Tension Certification from Westmoreland Mechanical Testing & Research, Inc.

Westmoreland Mechanical Testing & Research Inc.
Specialists in the Aviation and Nuclear Fields

Old Route 30, Westmoreland Drive
P.O. Box 388, Youngstown, Pa. 15696-0388 U.S.A.
Telephone: 412-537-3131 Fax: 412-537-3151

8 September 1993
Corrected 2 August 1994

MRC Bearings
Falconer Plant
Maroco Road
Falconer, NY 14733

Page 1 of 2
WMT&R Report 3-07160
P.O. No. 0202023079
Shipping Auth. 109895
Req. No. 55164

Attention: Mr. Ray Jones

Subject: Sharp Notch Tension Testing and Hydrogen Embrittlement Relief Testing of Submitted Material

Introduction:

Ten (10) samples, submitted as M50 material, identified as Sample Nos. 1 through 10, were received in the laboratory for sharp notch tension testing and hydrogen embrittlement relief testing. Sample Nos. 1, 3, and 4 were unplated and Sample Nos. 5, 6, 7, 8, 9, and 10, were chrome plated and tested as hydrogen embrittlement relief tests. Sample No. 2 was also chrome plated but was not tested.

Results:

Hydrogen Embrittlement Relief

Sample Nos. 5, 6, 7, 8, 9, and 10 were subjected to a sustained static tensile load (7537.9 lbs.) equal to 75 percent of the ultimate notch tensile strength (174086 PSI) for 200 hours without failure, (ultimate notch tensile strength (232115 PSI) was determined by averaging the results of the three (3) notch tensile tests). The six (6) samples were then visually examined at 10X magnification with an illumination of 1100 Lux (1X) with no evidence of cracking.

NOTE: Liquid penetrant examination of the base metal for cracks has not been performed.

At your service

Robert J. Sitko

Robert J. Sitko
Tech Service Manager

Approved by

James D. Rossi
Vice President

sml

Figure A–5. Hydrogen Embrittlement Test Results from Westmoreland Mechanical Testing & Research, Inc.

REPORT

Bridgeport Testing Laboratory, Inc.

INDUSTRIAL CHEMISTS · METALLURGISTS · CONSULTANTS

35 WILLOW ST. • BRIDGEPORT, CT 06610 • (203) 384-0361
FAX (203) 384-1822

FOR	Armoloy Of CT Inc. 151 Enterprise Drive Bristol CT 06011-0365 Attn: J. Graham	DATE	06-30-1993
		TEST NO.	931840
TEST TO	AMS 2438	P.O. NO.	4960 Page 1 of 1

Description: 4 x 4 Plates

Tank # 1

Taber Abrasion Test - 5,000 cycles CS-10 Wheels (1000 g load)

Weight Loss:

#1	1.0 mg
#2	1.1 mg
#3	0.9 mg
Total	3.0 mg

For Tests Performed:
Sample(s) submitted conform(s) to Specification(s) listed

WE CERTIFY THAT THIS IS A TRUE COPY OF OUR RECORDS
SIGNED FOR BRIDGEPORT TESTING LABORATORY, INC. BY:

Michael S Morris
its President

Checks and Calibrations of Equipment used for the above tests meet or exceed the requirements of:
PWA MCL Manual Section F-23 Mil I 45208A

NOTE: The recording of false, fictitious, or fraudulent statements or entries on this document may be punished as a felony under Federal Statutes including Federal Law Title 18, Chapter 34.

Semi-Quantitative Spectrographic Examination is an approximation of material identity. It is not a positive identification, and should be used for conformation purposes only. Where positive identification is necessary, complete chemical analysis should be requested.

This report is submitted with the understanding that it is not to be reproduced for advertising or other purposes over our signature without express written permission from us.

The liability of Bridgeport Testing Laboratory, Inc. concerning any use of these results shall be limited to the lower of either, the cost of testing, or the cost of the material involved.

Figure A–6. Taber Wear Test Results from Bridgeport Testing Laboratory, Inc.

Appendix B MRC Round No. 2 Supplemental Data

Westmoreland Mechanical Testing & Research Inc.
Specialists in the Aviation and Nuclear Fields

Old Route 30, Westmoreland Drive
P.O. Box 388, Youngstown, Pa. 15696-0388 U.S.A.
Telephone: 412-537-3131 *Fax: 412-537-3151*

20 April 1995

Page 1 of 2

MRC Bearings
402 Chandler Street
P.O. Box 280
Jamestown, NY 14702-0280

WMT&R Report 5-03006
P.O. No. 0202039383
Packing Slip: 1237

Attention: Patricia E. Wilson

Subject: Salt Spray Test per ASTM B117, AMS 2438, and Purchase Order Requirements

Introduction:

One (1) specimen, identified as Sample No. 1, submitted as a 309-size inner ring GE TDC 18, was received in the laboratory, and tested for a period of 24 hours in a salt fog per ASTM B117, AMS 2438 and Purchase Order Requirements. During the test, the sample was in a standing up position approximately 25 degrees from the vertical and the sample ID numbers that were on one side of the ring were facing down.

Results:

Upon completion of the test, the sample was gently washed in cool, clean water, and dried per specification requirements. The sample was then immediately examined and showed numerous rust spots on its surface. Due to the presence of these rust spots, the specimen identified as Sample No. 1, submitted as a 309-size inner ring GE TDC 18, is unacceptable per AMS 2438.

At your service

Andrew M. Wisniewski
Plant Manager

mls

Figure B–1. Corrosion Test Results from Westmoreland Mechanical Testing & Research, Inc.

Westmoreland Mechanical Testing & Research Inc.
Specialists in the Aviation and Nuclear Fields

Old Route 30, Westmoreland Drive
P.O. Box 388, Youngstown, Pa. 15696-0388 U.S.A.
Telephone: 412-537-3131 Fax: 412-537-3151

11 October 1995

MRC Bearings
402 Chandler St.
P.O. Box 280
Jamestown, NY 14702-0280

WMT&R Report No. 5-09523
P.O. No. 0202039383

Attention: Patricia E. Wilson

Subject: Salt Spray Test per ASTM B117, AMS 2438 Section 3.3.5, and P.O. Requirements.

Introduction:

One (1) specimen, identified as S/N No. 149, submitted as a 309-size inner ring GE TDC 31 BH87A, was received in the laboratory, and tested for a period of 24 hours in a salt fog at 95 degrees F per ASTM B117, AMS 2438 Section 3.3.5, and P.O. Requirements. It should be noted that the ring was tested with exceptions to AMS 2438. These exceptions are found in the Customer's Purchase Order. During testing, the ring was in a standing up position approximately 20 degrees from the vertical with the "S/N 149" numbers engraved on the sample being at the top. The surface with the "S/N 149" engraved on it was leaning towards the horizontal and was facing up.

Results:

Upon completion of the test, the sample was gently washed in cool, clean water, and dried per specification requirements. The sample was then immediately examined and showed numerous rust spots on its surface. Due to the presence of these rust spots, the specimen identified as S/N No. 149, submitted as a 309-size inner ring GE TDC 31 BH87A is unacceptable per AMS 2438 Section 3.3.5.

All testing was performed in accordance with the WMT&R Quality Assurance Manual Rev. 8 dated 5/3/93.

At your service

Andrew M. Wisniewski
Plant Manager

pmh

Figure B–2. Corrosion Test Results from Westmoreland Mechanical Testing & Research, Inc.

Westmoreland Mechanical Testing & Research Inc.
Specialists in the Aviation and Nuclear Fields

Old Route 30, Westmoreland Drive
P.O. Box 388, Youngstown, Pa. 15696-0388 U.S.A.
Telephone: 412-537-3131 Fax: 412-537-3151

20 April 1995

MRC Bearings
402 Chandler Street
P.O. Box 280
Jamestown, NY 14702-0280

WMT&R Report 5-03006
P.O. No. 0202039383
Packing Slip: 1237

Attention: Patricia E. Wilson

Subject: Embrittlement Relief Testing

Introduction:

Sample Nos. 1, 2, and 3 of M50 material were subjected to a sustained static tensile load of 6,145.1 pounds (174,086 psi), equal to 75% of the ultimate notch tensile strength, which was previously determined to be 232,115 psi, an average of three (3) notch tensile tests. Sample No. 2 broke prematurely in 2.5 hours. The remaining two (2) samples were retested under the same test conditions for 200 hours without failure. The samples were then visually examined at 4X to 25X magnification with no evidence of cracking.

Note: Liquid penetrant examination of the base metal for cracks has not been performed.

At your service

Robert J. Sitko

Robert J. Sitko
Tech Service Manager

mls

Figure B–3. Sharp Notch Tension Certification from Westmoreland Mechanical Testing & Research, Inc.

Appendix C SBB Round No. 1 Supplemental Data

DIRATS
LABORAT...

RECEIVED
SPLIT BALLBEARING
SEP 12 1994

TEST REPORT

Gary Ames
Split Ballbearing Division
MPB Corporation
Highway Four
Lebanon, NH 03766

Report Number	208120
Report Date	9-SEP-94
Page	1 of 1
Client Number	778350
Client Order	79272

RECEIVED	1 Part Approx. 1 7/8" dia.
IDENT AS	Item #150127
MATERIAL	Chrome Plated
CONDITION	*
TEST TO	AMS 2438 and Client Instructions
TEST PER	*
PURPOSE	*
PHONE	603-448-3000

PROPERTIES AS SUPPLIED

SALT SPRAY CORROSION TEST PER ASTM B117, 95 DEG F, 5% SOLUTION

TEST DURATION 24 HRS — Disp
No evidence of base metal corrosion. — For Info

NADCAP

WE CERTIFY THIS IS A TRUE COPY OF OUR RECORDS
Signed for J. Dirats and Co. by Eric Dirats, Audit Manager
NOTE: The recording of false, fictitious or fraudulent statements or entries on this document may be punished as a felony under federal law.

41 AIRPORT ROAD P.O. BOX 39 WESTFIELD, MA 01086-0039 FAX 413-568-1453 413-568-1571

Figure C–1. Corrosion Test Results from Dirats Laboratories.

REPORT

Bridgeport Testing Laboratory, Inc.

INDUSTRIAL CHEMISTS · METALLURGISTS · CONSULTANTS

35 WILLOW ST. · BRIDGEPORT, CT 06610 · (203) 384-0361
FAX (203) 384-1822

FOR	Armoloy of CT Inc. 151 Enterprise Drive Bristol CT 06011-0365 Attn: J. Graham	DATE	07-30-1993
		TEST NO.	932004
TEST TO	AMS 2438	P.O. NO.	4967CG

Description: 4 x 4 Plates

Tank # 4

Taber Abrasion Test - 5,000 cycles CS-10 Wheels (1000 g load)

Weight Loss:

#1	1.4 mg
#2	2.0 mg
#3	1.6 mg
Total	5.0 mg

For Tests Performed:
Sample(s) submitted conform(s) to Specification(s) listed.

RECEIVED
AUG 05 1993
By__________

WE CERTIFY THAT THIS IS A TRUE COPY OF OUR RECORDS
SIGNED FOR BRIDGEPORT TESTING LABORATORY, INC BY

Michael S Morris
its President

Checks and Calibrations of Equipment used for the above tests meet or exceed the requirements of:
PWA MCL Manual Section F-23 Mil I 45208A

Figure C–2. Taber Abraision Test Results from Bridgeport Testing Laboratory, Inc.

Appendix D SBB Round No. 2 Supplemental Data

DIRATS

TEST REPORT

Gary Ames
Split Ballbearing Division
MPB Corporation
Highway Four
Lebanon, NH 03766

Report Number	231901
Report Date	28-NOV-95
Page	1 of 1
Client Number	778350
Client Order	35207

RECEIVED	2 Parts
IDENT AS	Item #160116 W. Ogden
MATERIAL	*
CONDITION	*
TEST TO	*
TEST PER	P/O Instructions
PURPOSE	*
FAX	603-443-5201

PROPERTIES AS SUPPLIED

SALT SPRAY CORROSION TEST PER ASTM B117, 95 DEG F, 5% SOLUTION

TEST DURATION 24 Hrs.
Sample shows isolated areas of rust spots.

Disp
For Info

NADCAP

WE CERTIFY THIS IS A TRUE COPY OF OUR RECORDS
Signed for J. Dirats and Co. by Eric Dirats, Audit Manager
NOTE: The recording of false, fictitious or fraudulent statements or entries on this document may be punished as a felony under federal law.

41 AIRPORT ROAD P.O. BOX 39 WESTFIELD, MA 01086-0039 FAX 413-568-1453 413-568-1571

Figure D–1. Corrosion Test Report from Dirats Laboratories.

HENRY SOUTHER LABORATORIES, INC.

24 TOBEY ROAD, BLOOMFIELD, CONN. 06002
TEL. (203) 242-6291 FAX 203-286-0634
ENGINEERS, METALLURGISTS and ANALYSTS

Armoloy of Connecticut, Inc.
PO Box 365
Bristol, Ct. 06011-0365
Attn: Jim Graham

September 14, 1994

We have the following report to make upon the sample received PO 3266

Sample	Mark
790496	3 Panels, 4" x 4", Cell #4, per AMS 2438, Para. 3.3.4.1

TABER ABRASION

SAMPLE NO.	WEIGHT LOSS - MILLIGRAMS/5,000 CYCLES
1	4.4 mg.
2	5.5 mg.
3	5.1 mg.
AVERAGE	5.0 mg.

SATISFACTORY PER AMS 2438

CONDITIONS OF TEST

WHEELS	-	CS10 CALIBRASE
LOAD	-	1,000 GRAMS
CYCLES	-	5,000

RECEIVED
SEP 19 1994
By_______

F21A

We certify that the above
is a true copy of our record.

HENRY SOUTHER LABORATORIES, INC.

Monroe Nair, Supervisor, EX. 205

Figure D–2. Taber Abraision Test Results from Henry Souther Laboratory, Inc.

W E I B U L L   P A R A M E T E R   E S T I M A T I O N

(M E D I A N   R A N K S)

TEST NUMBER - G.E. RAMTIP 207BB TEST M50 BASELINE

NUMBER TESTED = 6

NUMBER	LIFE	DISPOSITION
1	619.80	FAILED
2	2500.00	SUSPENDED
3	2500.00	SUSPENDED
4	2500.00	SUSPENDED
5	4030.60	FAILED
6	4925.00	SUSPENDED

NUMBER FAILED = 2   NUMBER SUSPENDED = 4

WEIBULL SLOPE	=	0.8307
CORRELATION COEFF.	=	1.0000
CHARACTERISTIC LIFE	=	8329.7700
L-10 LIFE	=	554.7550
L-50 LIFE	=	5358.1400
EST.AVG. LIFE	=	9196.9800

THIS IS A FIRST IN 4 TEST

NOTE: THE ABOVE ESTIMATES ARE FOR THE SUDDEN DEATH LINE
THE FOLLOWING ESTIMATES ARE FOR THE POPULATION LINE

SLOPE	=	0.8307
L-10 LIFE	=	2943.6200
L-15.91 LIFE	=	5358.1400
65% LOWER LIMIT	=	2709.2300
65% UPPER LIMIT	=	9580.9500
90% LOWER LIMIT	=	1483.9300
90% UPPER LIMIT	=	% 14117.9
L-50 LIFE	=	% 28431
CHARACTERISTIC LIFE	=	% 44198.9
EST. AVG. LIFE	=	% 48800.6

Figure D–3. Weibull Parameter Estimation – M50 Baseline.

W E I B U L L   P A R A M E T E R   E S T I M A T I O N

(M E D I A N   R A N K S)

TEST NUMBER - G.E. RAMTIP 207BB TEST GROUP#1 TDC

NUMBER TESTED = 6

NUMBER	LIFE	DISPOSITION
1	41.50	FAILED
2	225.50	FAILED
3	1825.40	FAILED
4	2293.30	FAILED
5	2710.40	FAILED
6	2844.20	SUSPENDED

NUMBER FAILED = 5　　NUMBER SUSPENDED = 1

WEIBULL SLOPE	=	0.5022
CORRELATION COEFF.	=	0.9648
CHARACTERISTIC LIFE	=	2903.3400
L-10 LIFE	=	32.8651
L-50 LIFE	=	1399.3600
EST.AVG. LIFE	=	5760.4700

THIS IS A FIRST IN 4 TEST

NOTE: THE ABOVE ESTIMATES ARE FOR THE SUDDEN DEATH LINE
THE FOLLOWING ESTIMATES ARE FOR THE POPULATION LINE

SLOPE	=	0.5022
L-10 LIFE	=	519.5550
L-15.91 LIFE	=	1399.3600
65% LOWER LIMIT	=	452.9230
65% UPPER LIMIT	=	3659.5700
90% LOWER LIMIT	=	167.3300
90% UPPER LIMIT	=	6949.0300
L-50 LIFE	=	% 22122
CHARACTERISTIC LIFE	=	% 45897.8
EST. AVG. LIFE	=	% 91065.7

Figure D–4. Weibull Parameter Estimation – Test Group No. 1.

W E I B U L L   P A R A M E T E R   E S T I M A T I O N

(M E D I A N   R A N K S)

TEST NUMBER - G.E. RAMTIP 207BB TEST GROUP#2

NUMBER TESTED = 6

NUMBER	LIFE	DISPOSITION
1	246.60	FAILED
2	500.80	FAILED
3	710.00	FAILED
4	1002.70	FAILED
5	1193.30	FAILED
6	2500.00	SUSPENDED

NUMBER FAILED = 5   NUMBER SUSPENDED = 1

WEIBULL SLOPE	= 1.5157
CORRELATION COEFF.	= 0.9974
CHARACTERISTIC LIFE	= 1052.1300
L-10 LIFE	= 238.3840
L-50 LIFE	= 826.1390
EST.AVG. LIFE	= 948.6310

THIS IS A FIRST IN 4 TEST

NOTE: THE ABOVE ESTIMATES ARE FOR THE SUDDEN DEATH LINE
THE FOLLOWING ESTIMATES ARE FOR THE POPULATION LINE

SLOPE	= 1.5157
L-10 LIFE	= 594.9610
L-15.91 LIFE	= 826.1390
65% LOWER LIMIT	= 568.5120
65% UPPER LIMIT	= 1136.0000
90% LOWER LIMIT	= 408.7550
90% UPPER LIMIT	= 1404.9000
L-50 LIFE	= 2061.8900
CHARACTERISTIC LIFE	= 2625.9200
EST. AVG. LIFE	= 2367.6100

Figure D–5. Weibull Parameter Estimation – Test Group No. 2.

W E I B U L L   P A R A M E T E R   E S T I M A T I O N

(M E D I A N   R A N K S)

TEST NUMBER - G.E. RAMTIP 207BB UNBAKED

NUMBER TESTED = 4

NUMBER	LIFE	DISPOSITION
1	28.60	FAILED
2	40.00	FAILED
3	196.10	FAILED
4	253.10	FAILED

NUMBER FAILED = 4   NUMBER SUSPENDED = 0

NUMBER

WEIBULL SLOPE	=	0.8552
CORRELATION COEFF.	=	0.9348
CHARACTERISTIC LIFE	=	151.7760
L-10 LIFE	=	10.9253
65% LOWER LIMIT	=	1.7903
65% UPPER LIMIT	=	38.6131
90% LOWER LIMIT	=	0.2658
90% UPPER LIMIT	=	79.5855
L-50 LIFE	=	98.8741
EST.AVG. LIFE	=	164.5000

Figure D–6. Weibull Parameter Estimation – Unbaked.

Appendix E Nodular Thin Dense Chrome Coating for Mainshaft Bearings Specification

The following is a reproduction of GE Aircraft Engine Specification F50TF91 "Nodular Thin Dense Chrome Coating for Mainshaft Bearings"

GE Aircraft Engines
Specification

SPECIFICATION NO. F50TF91
ISSUE NO. S0
DATE December 22, 1992
PAGE 1 OF 11
CAGE CODE 07482
SUPERSEDES NEW

NODULAR THIN DENSE CHROME COATING FOR MAINSHAFT BEARINGS

1. SCOPE

1.1 Scope. This specification establishes the requirements for electroplated nodular thin dense chrome (NTDC) coating for mainshaft, M50 (AMS 6491) and M50NiL (AMS 6278) bearing rings and rollers.

1.1.1 Classification. This specification contains the following class(es). Unless otherwise specified the requirements herein apply to all classes.

CLASS A:

1.2 Definitions. For purposes of this specification the following definitions shall apply:

Coupon - A test piece of material representative of that area of the part to be plated which may be used to destructively evaluate the plating process. Material is the same in composition, heat treatment, and surface finish as the part to be plated.

Functional Surfaces - Surfaces of the bearing that receive rolling contact stresses during operation of the bearing. These surfaces include ball/roller tracks of bearing races and the cylindrical surface of rollers. (See Figure 1 surfaces E)

Purchaser - The procuring activity of GE Aircraft Engines (GEAE) that issued the procurement document invoking this specification. When this specification is invoked by a U. S. Government purchasing activity (or such activity's designee) the Purchaser shall mean such activity or designee as the case may be.

Shoulder Areas - Surfaces that are adjacent to functional surfaces. (See Figure 1 surface F)

Supplier - Source other than GE Aircraft Engines (GEAE) who provides material, parts or services, for incorporation into GEAE products.

PREPARED	REVIEWED	APPROVED BY:
S. A. Schwarz	Mike Pino	[X] EVENDALE
APPROVED	DISTRIBUTION 10A	[X] LYNN

GT9166 (3-88)

GE Aircraft Engines
Cincinnati, OH 45215-6301

Technical Plan - A document prepared by the Supplier and approved by the Purchaser which includes as a minimum applicable information for each part number concerning: bath constituents, facilities, equipment, processing method, sketches of lift, and electrical contact fixtures. Set up and rack design, processing steps, temperatures, time, controls and post heat treatment procedures.

1.3 Regulated Materials. The regulated material(s) shown below, are referenced within this specification. Respective regulatory requirements in accordance with P2TF1, CL-A, shall be complied with.

(a) Chromium and Compounds

2. APPLICABLE DOCUMENTS

2.1 Issue of Documents. The following documents form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue shall apply.

AEROSPACE MATERIAL SPECIFICATIONS

AMS 2438	Chromium Coating - Thin Hard Dense Deposit
AMS 6278	M50NiL Bearing Steel
AMS 6491	M50 Bearing Steel

AMERICAN SOCIETY FOR TESTING MATERIALS

ASTM B 117	Salt Spray (Fog) Testing
ASTM B 487	Measurement of Metal and Oxide Coating Thicknesses by Microscopic Examination of a Cross Section
ASTM F 519	Mechanical Hydrogen Embrittlement Testing of Plating Processes and Aircraft Maintenance Chemicals

FEDERAL STANDARDS

FED-STD-141	Paint Varnish, Lacquer, And Related Materials; Methods For Sampling And Testing.

GE AIRCRAFT ENGINES PHOTOGRAPHS

9207001	15X and 50X Nodular Thin Dense Chrome Coating (NTDC)
9207002	500X Nodular Thin Dense Chrome Coating

GE AIRCRAFT ENGINES SPECIFICATIONS

P1TF33	Preparation of Technical Plans for Coating Applications.

3. REQUIREMENTS

3.1 General

3.1.1 Sources. Coated parts shall be procured only from Suppliers approved by the Purchaser.

3.1.2 Technical Plan. A Technical Plan for the control and operation of the chrome electro-deposition process shall be prepared in accordance with P1TF33, CL-A, and shall be submitted for each specific part number or part family by the Supplier and approved by the Purchaser before the plating of parts. The Technical Plan shall have a unique identification including revision control.

3.1.2.1 Coverage. The Technical Plan shall cover, as a minimum, the following elements.

(a) Part number or part family
(b) Process sequence, including duration range of each operation and maximum delay times
(c) Type of power source
(d) Fixtures, including electrodes and lift fixtures
(e) Tank dimensions and the number of parts processed simultaneously
(f) Bath chemistry, temperature, concentration ranges including contaminants, and solution analysis procedures
(g) Masking methods and materials, include sketches or photographs
(h) Surface preparation
(i) Delay time between cleaning and plating
(j) Plating current density and cycle time.
(k) Post plating cleaning, unmasking, and drying procedures
(l) Maskant interface conditions
(m) Electrode design and placement, including materials
(n) Description and placement of coupons
(o) Rinsing and maskant removal method(s)
(p) Heat treatment method, equipment and control, including plans for insuring that the post bake cycle occurs within the prescribed delay and is carried out using the correct temperature and time
(q) Stripping procedure including bake cycle
(r) Control method of assuring pre-plated and post-plated quality.
(s) Control limits shall be specified for all applicable processing operations. Modification plans shall be defined for control limit violations. Procedures for documenting and processing control limit violations shall be identified.
(t) Process qualification tests including details of the methods, number of samples, and frequency of the tests.
(u) Acceptance tests for production hardware.

Note: Should any of the Technical Plan elements be considered proprietary by the supplier a control number and revision shall be listed instead of the actual parameters. The complete detailed processing and supporting documents shall be available for review upon Purchaser request.

3.1.2.2 Process Changes. Any change to the established Technical Plan shall be approved by the Purchaser before the incorporation of the change.

3.1.3 Magnetic Particle Inspection. When magnetic particle inspection is required by the part drawing, the part(s) shall be inspected both before and after plating. The part(s) shall be demagnetized after each inspection.

3.1.4 In-Process Storage. Parts in queue for processing or shipment to the Purchaser shall not be stored in the vicinity of chemicals capable of causing corrosion. The parts shall also be protected from contamination by abrasives, metal particles, etc.

3.1.5 Test Specimens. Coupons representing the same geometry as production parts may be used. In addition, test bars as defined by AMS 2438 may be used where appropriate. Coupons intended to represent production hardware shall be coated using the same process parameters and plating setup as the parts they represent. Properties requiring destructive evaluation shall be evaluated using scrap hardware, production hardware or coupons. All specimen size, material, heat treatment and configuration require approval by the Purchaser.

3.1.6 Sampling. Sampling requires justification using statistical methods. Sampling shall be in accordance with an approved Technical Plan.

3.1.7 Plating Evaluation

3.1.7.1 Responsibility. The Supplier shall supply all samples for test, perform all required evaluations, and retain the test data.

3.1.7.2 Certificate Of Test. A certificate of test representing each part plated to this specification shall be submitted by the Supplier and mailed with or preceding the shipment of parts. This certificate shall give the results of all required tests and inspections, and shall show that the results are in accordance with the requirements of this specification. Additionally the certificate shall show the following.

(a) Purchase order number
(b) Detailed part number and serial number(s)
(c) Technical Plan identification and revision
(d) Quantity of parts plated
(e) Date of coating
(f) Coating lot number
(g) Time between the end of the cleaning operation and commencement of the plating operation
(h) Time and temperature at which parts were baked
(i) Time between the end of the plating operation and commencement of the baking operation
(j) Number of strip and replating operations, if any.
(k) Results of acceptance tests with variable data.
(l) Any other special instructions or specifications required by the Purchase order
(m) The applicable GEAE specification number(s), class(es), and issue number(s) including this specification

3.1.7.3 Sample Part Approval. Plated parts shall be approved by the Purchaser, before production parts are supplied. Sample parts or coupons shall be processed in accordance with the proposed Technical Plan. The results of tests on sample parts or coupons shall represent the properties of the plating on production parts.

3.2 Part Preparation Before Chrome Plating. The requirements for part preparation before plating as described in the following subparagraphs shall be documented in the Technical Plan.

3.2.1 Surface Condition For Plating. Surface preparation methods for preparing the parts surface(s) for chrome plating shall be in accordance with the drawing requirements for size, surface finish and in accordance with the Technical Plan.

3.2.2 Heat Treatment. All heat treatment processes, except Embrittlement Relief (See 3.4.2), shall be completed before coating.

3.2.3 Machining. Components shall have all machining, grinding, honing, etc. completed before coating or as approved by the Purchaser.

3.2.4 Stress Relieve. Components shall be stress relieved before cleaning for coating. Stress relief shall be performed at 375°F ± 25 (190.6°C ± 14) for not less than 3 hours.

3.2.5 Masking. Unless otherwise approved by the Purchaser, all surfaces which are not intended to be plated shall be masked. Masking may be sequenced after the cleaning in accordance with 3.2.7.

3.2.6 Storage After Finish Grinding. All component surfaces shall be covered with rust preventative oil and packaged in a manner to prevent damage during transport between finish grind operations and plating operations.

3.2.7 Cleaning. Parts, before coating shall have chemically clean surfaces, prepared with minimum abrasion, erosion, or pitting. After cleaning parts shall be stored in a manner that prevents oxidation from forming on the surfaces to be coated.

3.3 Chrome Plating Process Requirements. The chrome plating process requirements as described in the following subparagraphs shall be documented in the Technical Plan.

3.3.1 Commencement Of Plating. Plating shall commence as soon as practical after cleaning and surface preparation in accordance with 3.2.7 and 3.2.1. The time delay between the final cleaning process and the initiation of plating shall not exceed the maximum delay time approved in the Technical Plan. Actual delay time shall be reported in the Certificate Of Test.

3.3.2 Plating Temperature and Chemistry. The plating bath shall be within ± 5°F (3°C) of the bath temperature detailed in the Technical Plan during plating. The chemistry and plating conditions shall be within limits as approved in the Technical Plan.

3.3.3 Plating - Electrical Arcing Prevention. To prevent arcing during plating, parts shall not be inserted, moved, or removed from the plating tank with the rectifier on.

3.3.4 Current Density And Cycle Time. The current density range, and the estimated deposition cycle time shall be as approved in the Technical Plan.

3.3.5 Process Interruption. If the plating process is interrupted (i.e., power failure) the parts shall be removed from the bath in accordance with 3.3.3. The parts shall be baked, stripped and replated in accordance with the Technical Plan.

3.4 Post Chrome Plating Procedures. The requirements for part processing and handling after plating described in the following subparagraphs shall be documented in the Technical Plan.

3.4.1 Part Cleaning And Unmasking. After plating, but before the embrittlement relief in accordance with 3.4.2, parts shall be unmasked, rinsed, and dried. If chemical cleaning is used, it shall be followed by a water rinse. Upon completion, all residues shall be removed from the part.

3.4.2 Embrittlement Relief. After being dried, parts shall be baked at a temperature between 375 - 450°F (190.6 - 232.2°C) for at least five hours. This treatment shall be performed within one hour after completion of the plating process. Baking shall be performed in an air recirculating oven. The Supplier shall retain a record of the baking operation and the delay time between end of plating and the start of baking.

3.5 Coating Properties/Conditions Of The Part

3.5.1 General. The test methods, procedures and data used to establish conformance to these requirements shall be described in the Technical Plan.

3.5.2 Plating Coverage. Unless otherwise specified on the purchase order or engineering drawing, the plating shall cover all surfaces.

3.5.3 Thickness

3.5.3.1 Functional Surface Thickness. For all functional surfaces thickness shall be 40 μinch (1.0 μm) to 100 μinch (2.5 μm).

3.5.3.2 Shoulder area Thickness. For shoulder areas thickness shall be 40 μinch (1 μm) to 250 μinch (6.3 μm)

3.5.3.3 Other Non-Functional Surfaces. For other surfaces, corners and edges, thickness shall be 40 μinch (1.0 μm) minimum or as specified by the drawing. For rollers, exception to complete coverage is allowed on ends where point contact was made during fixturing. Point contacts shall not be used on any functional surface.

3.5.3.4 Slots, Grooves And Holes. No requirements are established for the thickness of the coating for slots and grooves less than 0.200 inch (5.08 mm) wide and holes less than 0.187 inch (4.74 mm) in diameter, but such areas shall not be masked to prevent coating unless approved by the Purchaser.

3.5.4 Surface Condition. All parts shall have the following surface condition.

3.5.4.1 Maskant Interface. Unplated areas of parts shall not exhibit staining or maskant residue related to the plating operation. Expected edge conditions at the maskant interface shall be as described in the Technical Plan.

3.5.4.2 Corrosion And Arcing Damage. Coated functional surfaces shall exhibit no corrosion or arc damage when examined with magnification not exceeding 5X.

3.5.4.3 Pits, Dents, Nicks, And Scratches. Pits, dents, nicks, and scratches shall be interpreted to the requirements of the uncoated part unless otherwise specified by the drawing or purchase order.

3.5.4.4 Other Imperfections. No cracks, peeling, discontinuities, porosity, solution stains, gas streaks, pinholes, or burn marks shall be allowed on coated surfaces when viewed visually with magnification not exceeding 5X. Slight discoloration resulting from baking is acceptable. Light frosted appearances where electrical contact was made are not cause for rejection so long as they are not present on functional surfaces.

3.5.5 Microscopic Surface Condition Evaluation. Functional surfaces and corners adjacent to functional surfaces shall be examined using assisted magnification. The sampling plan for these examinations shall be given in the Technical Plan.

3.5.5.1 Evaluation At 15X-50X Magnification. Coated functional surfaces and corners adjacent to functional surfaces shall be free of cracks, pinholes, peeling, porosity, discontinuities or irregular isolated chromium deposits when examined with magnification ranging from 15X to 50X. The magnification shall be specified in the Technical Plan. Irregular chrome deposits and clusters shall be interpreted to photo numbers 9207001 and 9207002.

3.5.5.2 Evaluation At 500X Magnification. When examined with 500X magnification coated functional surfaces shall have complete nodularity as defined in photo 9207002-A and 9207002-B. These surfaces shall be free of cracks and poor nodularity or chrome clusters as shown in photo 9207002-C and 9207002-D. There shall be no visible cracking or discontinuities in the corners adjacent to functional surfaces.

3.5.5.3 Evaluation At 1000X Magnification. Coating integrity shall be confirmed by metallographic examination of representative cross sections for functional surfaces. The test part or coupon representing the coating and substrate shall be in the as-polished condition and examined at 1000X. No debonding, porosity, cracks, or other condition detrimental to the coating is allowed.

3.5.6 Hydrogen Embrittlement. The coating process shall be non-embrittling, as defined by ASTM F 519. After being tested in accordance with 4.2.4 the part shall conform to 3.5.3.

3.5.7 Adhesion And Thermal Shock Resistance. The coating shall be firmly bonded to the base metal and shall be able to conform to the requirements in the following subparagraphs:

3.5.7.1 Adhesion. Test specimens shall not show separation from base metal when tested in accordance with 4.2.3

3.5.7.2 Thermal Shock. Test specimens shall meet the requirements of 3.5.4 and 3.5.5 after being tested in accordance with 4.2.5.

3.5.8 Corrosion Resistance. The coating shall exhibit at least a 5X greater resistance to pitting when examined with up to 5X magnification after testing in accordance with 4.2.6.

3.5.9 Wear Resistance. A standard Taber specimen tested in accordance with 4.2.7 shall show a wear index based on the weight-loss method, in accordance with FED-STD-141 Method 6192, of less than 1.2 average, or 6 mg, for three consecutive tests.

3.5.10 Residual Stress Properties. The coating shall be deposited so that it is in a state of compression. Coatings deposited in tension are cause for rejection.

3.5.11 Surface Roughness. The coating shall have a surface roughness on functional areas of 1-8 μinch Ra (0.025-0.2 μm).

3.5.12 Rolling Contact Properties. The coating shall not reduce the rolling contact fatigue life of the base metal. When tested in accordance with 4.2.9 coated bearings shall exhibit a fatigue life at least equal to uncoated bearings. No coating adhesion failures shall be allowed.

4. QUALITY ASSURANCE

4.1 Process Qualification Tests. The following coating characteristics shall be determined using the test methods in 4.2 and in accordance with the Technical Plan.

(a) Plating Thickness
(b) Surface Condition
(c) Adhesion
(d) Hydrogen Embrittlement
(e) Thermal Shock
(f) Corrosion Resistance
(g) Wear Resistance
(h) Residual Stress
(i) Rolling Contact Fatigue
(j) Surface Roughness
(k) Microscopic Surface Condition

4.1.1 Acceptance Tests For Production Hardware. As a minimum the following coating characteristics shall be determined using the test methods in 4.2 and in accordance with the Technical Plan.

(a) Plating Thickness
(b) Surface Condition
(c) Adhesion

4.2 Tests

4.2.1 Plating Thickness. Thickness shall be in accordance with 3.5.3 using methods approved in the Technical Plan. For acceptance testing, variable data is required. Destructive thickness measurements of a coupon in accordance with ASTM B 487, shall be used to confirm the accuracy of non-destructive techniques.

4.2.2 Surface Condition. Surface condition shall be evaluated to the plan approved in the Technical Plan and meet the requirements of 3.5.4 and 3.5.5.1.

4.2.3 Adhesion. Shall be tested in accordance with AMS 2438 or as approved in the Technical Plan.

4.2.4 Hydrogen Embrittlement. Hydrogen Embrittlement shall be determined by a 200 hour test tensile test with a constant load equal to 75 percent of the notched ultimate tensile strength in accordance with ASTM F 519 except that, when approved by Purchaser, a suitable electronic meter or gauge may be used. Specimen configuration shall be the notched bar tensile type 1A. When approved by the Purchaser smaller sizes may be used. The tensile bar material shall be in the fully hardened and tempered condition.

4.2.5 Thermal Shock. Thermal shock shall be determined using a coated inner ring (Figure 1 item B) in accordance with the following sequence.

(a) Quench to between -65°F and -130°F (-53.9°C and -90.0°C) and hold for 45 minutes ± 15.
(b) Immediately place in a furnace at 600°F ± 25 (315.6°C ± 14) and hold for 45 minutes ± 15.
(c) Remove from furnace and allow to stabilize to room temperature.
(d) Repeat steps (a) thru (c) sequentially for a total of 10 cycles.
(e) Examine coated surfaces in accordance with 3.5.4 and 3.5.5 of this specification.

4.2.6 Corrosion Resistance. Corrosion resistance test shall be a 24 hour salt spray test in accordance with ASTM B 117. The test specimen shall be an inner ring or part of an inner ring. See Figure 1 item B.

4.2.7 Wear Resistance. Wear resistance shall be tested in accordance with FED-STD-141, Method 6192, using a Taber specimen (defined in FED-STD-141). The specimens shall be cleaned, coated, and post-treated with the parts being represented. Each specimen shall be subjected to 1000 g load for 5000 cycles using a Taber abrasion tester with CS-10 wheels.

4.2.8 Residual Stress. Residual stress confirmation shall be obtained by the use of X-ray diffraction methods or a method approved in the Technical Plan.

4.2.9 Rolling Contact Fatigue. Testing shall compare the L10 fatigue life of both coated and uncoated bearings using Weibull statistical methods. Method and sizes shall be approved by the Purchaser.

4.2.10 Surface Roughness. Surface roughness shall be determined using a contact stylus method as approved in the Technical Plan.

4.2.11 Microscopic Surface Condition. Functional surfaces and corners adjacent to functional surfaces of coated part(s) shall be examined using assisted magnification. Evaluations shall be done at 15X to 50X and 500X and meet the requirements of 3.5.5.1 and 3.5.5.2 respectively. At 1000X test part(s) or coupon(s) representing the coating and substrate shall be used for metallographic examination. A representative cross section for functional surfaces shall be examined in the as-polished condition and meet the requirements of 3.5.5.3.

5. PACKAGING

5.1 Packing. All material shall be packed to prevent damage, loss or contamination during handling, shipping or storage.

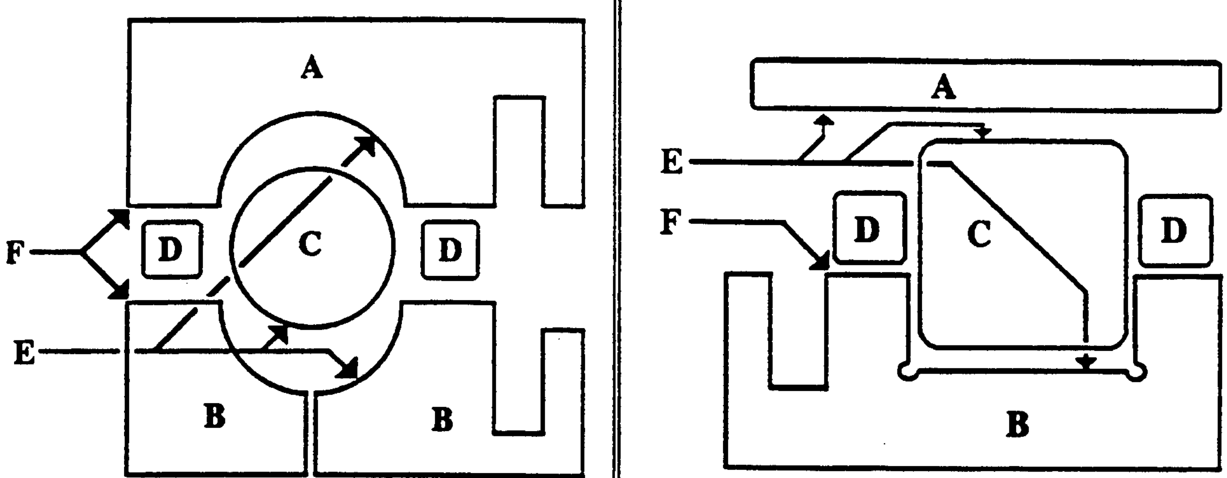
5.2 Marking. Each shipment shall be legibly marked with the purchase order number, supplier's name, quantity, part number, batch or lot number and this GE specification number, class and issue number.

6. NOTES

This section is not applicable.

Typical Bearing Cross Sections

Ball Bearing | **Roller Bearing**



A. Outer Ring

B. Inner Ring

C. Balls Or Rollers

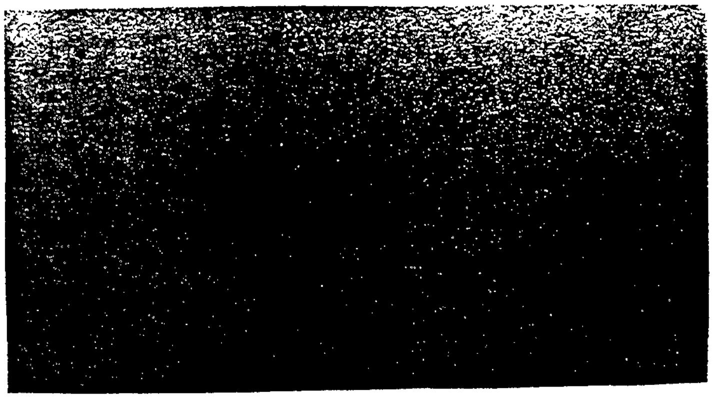
D. Cage

E. Functional Surface, Raceways, And All Other Rolling Contact Surfaces

F. Shoulder Area

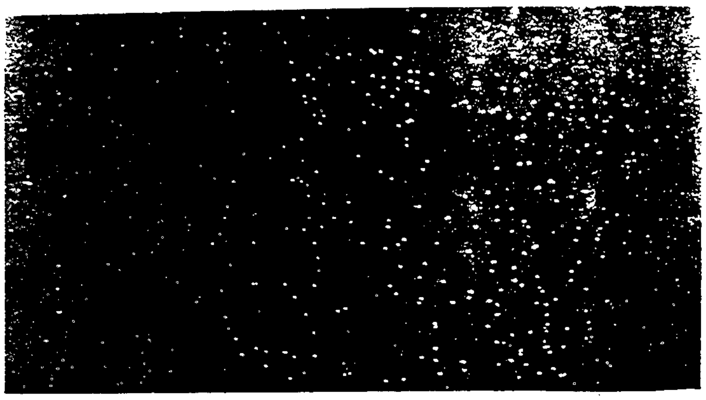
Figure 1

ALTERATION OF NEGATIVE PROHIBITED



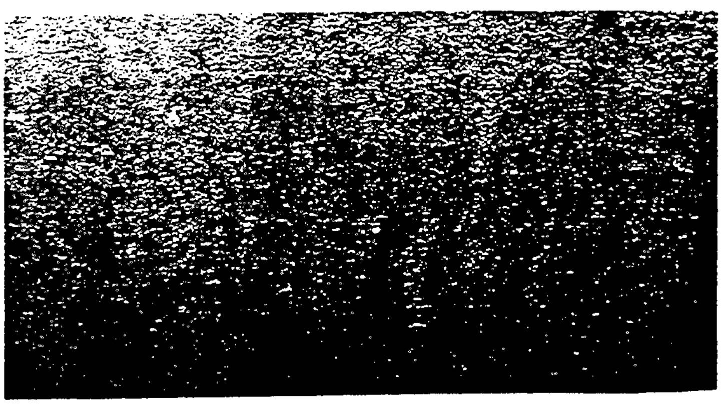
15X

Acceptable NTDC



15X

Unacceptable NTDC



50X

Unacceptable NTDC

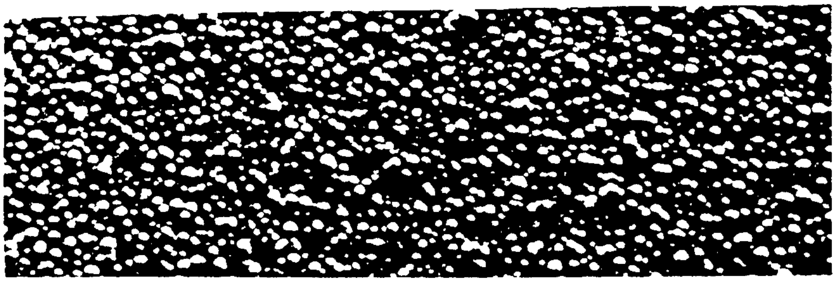
Note: The examples of unacceptable NTDC do not represent the only types that can occur.

REF. GE SPECIFICATION

GENERAL ELECTRIC AIRCRAFT ENGINES CINCINNATI, OH 45215	FSCM NO. 07482	PHOTO NUMBER **9207001**

(MS&D, 02-92)

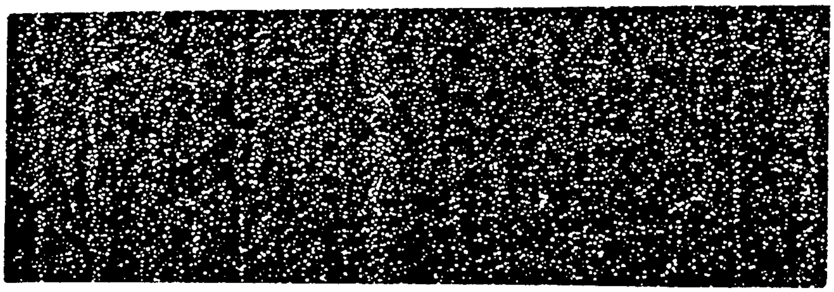
ALTERATION OF NEGATIVE PROHIBITED



A) 500X

Acceptable NTDC

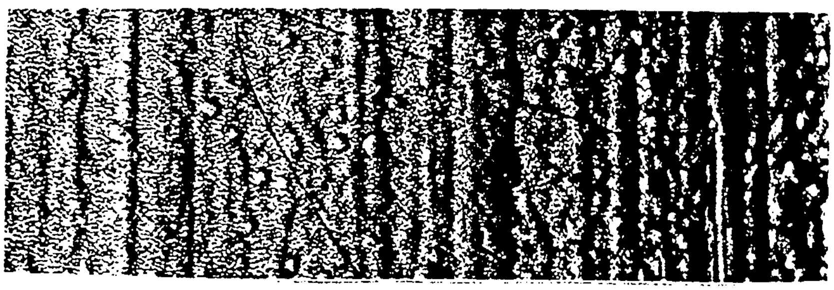
Maximum Nodularity



B) 500X

Acceptable NTDC

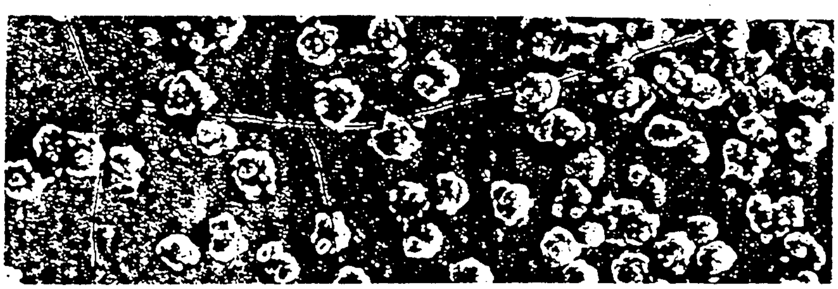
Minimum Nodularity



C) 500X

Unacceptable NTDC

Poor Nodularity and Cracking



D) 500X

Unacceptable NTDC

Chrome Clusters and Cracking

Note: The examples of unacceptable NTDC do not represent the only types that can occur.

REF. GE SPECIFICATION

GENERAL ELECTRIC AIRCRAFT ENGINES CINCINNATI, OH 45215	FSCM NO. 07482	PHOTO NUMBER 9207002

Appendix F Bearing Test Summary

Table F.1 Full Scale Bearing Test Summary

Test	Supplier	GE Part No. and Serial No.	Race/Coating/Cage Plate Materials	Results
Operational Endurance	SBB	1665M43P01 MABS9632	M50/TDC/Silver	2,000 hr (Suspended)
		1665M43P01 MABS9636		
		1665M45P01 MABS6867	M50Nil/TDC/Silver	
		1665M45P02 MABS6755	M50Nil/TDC/Phosphate	
	MRC	1665M42P01 MDACE702	M50/TDC/Silver	
		1665M42P01 MDACE703		
Contamination	SBB	1461M15P06 MABS1887	M50Nil/TiN/Silver	96.9 hr (O.R. Spalling)
		1665M45P02 MABS6754	M50Nil/TDC/Phosphate	96.9 hr (Acceptable)
	MRC	1665M42P01 MDACE704	M50/TDC/Silver	1,000 hr (Suspended)
		1665M42P01 MDACE705		
		9732M10P16 MDA713JV	M50/Silver	126.3 hr (O.R. Spalling)
		9732M10P16 MDA604JV		126.3 hr (O.R. Pitting)
Oil Off	MRC	9732M10P16 MDA606JV	M50/Silver	88 seconds
		1665M42P01 MDACE694	M50/TDC/Silver	119.8 seconds
	SBB	1461M15P06 MABS1881	M50Nil/TiN/Silver	83.6 seconds
		1665M45P01 MABS6865	M50Nil/TDC/Silver	119.4 seconds

Table F.1 Full Scale Bearing Test Summary (concluded).

Test	Supplier	GE Part No. and Serial No.	Race/Coating/Cage Plate Materials	Results
Oil Off	MRC	9732M10P16 MDA607JV	M50/Silver	32.0 seconds
		1665M42P01 MDACE695	M50/TDC/Silver	90.4 seconds
	SBB	1461M15P06 MABS1882	M50Nil/TiN/Silver	35.5 seconds
		1665M45P02 MABS6751	M50Nil/TDC/Phosphate	25.7 seconds
Skid	MRC	9732M10P16 MDA610JV	M50/Silver	No Skid Damage
		1665M42P01 MDACE701	M50/TDC/Silver	Skid Damage
		9732M10P16 MDA602JV	M50/Silver	No Skid Damage
		1665M42P01 MDACE700	M50/TDC/Silver	
Induced Defect	MRC	9732M10P16 MDA605JV	M50/Silver	78.1 hr (Cage Failure)
		1665M42P01 MDACE693	M50/TDC/Silver	100 hr (Suspended)
	SBB	1461M15P06 MABS1879	M50Nil/TiN/Silver	55.7 hr (Cage Failure)
		1665M45P01 MABS6757	M50Nil/TDC/Silver	50.2 hr (Cage Failure)
Thermal Cycle	MRC	1665M42P01 MDACE697	M50/TDC/Silver	Successful
	SBB	1665M45P01 MABS9638	M50Nil/TDC/Silver	
		1665M46P01 MABR9919	M50/TDC/Silver	
Corrosion Resistent	MRC	SNR00173	M50	Extensive Corrosion
		MDA605JV		
		MDACE697	M50/TDC	4 Pits on Face
	SBB	MABS9632		No Corrosion
		MABS6867	M50Nil/TDC	
		X097		

Table F.2 Full Scale Bearing Engine Test Summary

Engine Test	Supplier	GE Part No. and Serial No.	Bearing	Results
583–103/4	MRC	1665M35P01 MRCR1925	No. 1R (O.R.)	813 hr (Acceptable)
		1665M36P01 MDACE691	No. 1R (I.R.)	
		1665M40P01 MDACE711	No. 2B	
	SBB	1665M45P02 MABS6757	No. 3B	813 hr (Skid Damage/Ball Spall)
		1665M46P01 MABR9915	No. 4R	281 hr (Acceptable)
		1665M49P01 MABS7506	No. 5R (O.R.)	
		1665M51P01 MABS6737	No. 5R (I.R.)	281 hr TDC Peeling
509–716/5	SBB	1665M52P01 MABS8952	No. 1R (O.R.)	449 hr (Assembly Damage)
	MRC	1665M36P01 MDACE689	No. 1R (I.R.)	
	SBB	1665M39P01 MABS6639	No. 2B	700 hr (Micro-peeling)
	MRC	1665M42P01 MDACE698	No. 3B	700 hr (Acceptable)
	SBB	1665M46P01 MABW5741	No. 4R	555 hr (O.R. Spalling)
		9340M16P04 MABR5416	No. 5R (O.R.)	555 hr (Acceptable)
		9502M14P08 MABR1654	No. 5R (I.R.)	